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UNIVERSITY OF ALBERTA

KINETICS OF BLENDING FOR SOLUBLE POLYMER ADDITIVES

BY

JORDI L. HEMSING Ⓒ

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

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The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled: KINETICS OF BLENDING FOR SOLUBLE POLYMER ADDITIVES submitted by: Jordi L. Hemsing in partial fulfillment of the requirement for the degree of MASTERS OF SCIENCE IN CHEMICAL ENGINEERING.

DEDICATION

I would like to dedicate this thesis to my parents in recognition of all the support (emotional and financial) you have given me throughout this endeavour. I wouldn't be who am today without your constant support and love.

Abstract

Filter aid polymers are widely used in the water treatment industry. They are added in very small quantities at significant expense. Their performance is variable, and there is a great deal of uncertainty in the "best practice" operation. Consistent results have proved difficult to obtain. Filter aid polymers used in water treatment applications are added prior to the filtration stage and are subjected to rapid mixing to achieve complete dispersion. If complete dispersion is not obtained before the polymer enters the filters, blockage of the top layer of the filter media occurs leading to rapid headloss development or "cap off". The polymers used in water treatment are soluble in water but may not be completely miscible under plant conditions. This study addresses a persistent industrial problem: dispersion of small quantities of polymer additives (stabilizers, dispersers, flocculants, polymer filter aids, etc.) in large quantities of process fluids.

To investigate the mechanism of mixing of filter aid polymers, the effect of mixing intensity, polymer concentration and water source were examined using a pilot plant. It was found that all of these variables have an effect on the dispersion of the polymer. In addition to testing these there factors, various impeller types and sizes were tested. The results from this testing did not correlate with established mixing variables, however, it was found that consistent results could be obtained when the mean residence time of the tank was greater than 75 batch blend times.

The results from the pilot plant experiments suggested that the properties of the polymer, such as viscosity, solubility and miscibility are important to polymer dispersion. It was found that the viscosity of the polymer was not a contributing

factor. This study shows that the polymer, which was found to be completely soluble in water under plant conditions at long times (24 hours), is partially miscible at shorter time scales (30 minutes). There is a resistance to dispersion that is due, in part, to the interpenetration of polymer coils in the feed solutions for the pilot plant. The kinetics of this process are comparable to kinetics of liquid-liquid dispersion at low dispersed phase fractions.

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NOMENCLATURE

C   Off bottom clearance, m

D   Impeller diameter, m

G   Mean shear rate, s^{-1}

h   Impeller height, m

H   Liquid height in the vessel, m

L   Length

N   Rotational speed, rpm

Np   Power number

P   Power input, W

Q   Volumetric flow rate, m^3/s

Re   Reynolds Number

T   Vessel diameter, m

V   Volume, m^3

V_I Impeller swept volume, m^3

W   Width

Symbols

ε Turbulent energy dissipation, m^2/s^3

$\bar{\varepsilon}$ Average power dissipation, m^2/s^3

ε_B Energy dissipation in the bulk, m^2/s^3

ε_I Energy dissipation at the impeller, m^2/s^3

η	microscale length of turbulence, m
μ	dynamic viscosity, kg m/s
ν	kinematic viscosity, m^2/s
θ_B	Blend time, s
θ_{Tank}	Tank circulation time, s
ρ	Density, kg/ m^3
τ	mean residence time, s

Chapter 1

Literature Review

1.0 Introduction

Water contains a heterogeneous mixture of substances which include living and nonliving, synthetic and natural, color and colorless, toxic and nontoxic, inorganic and organic, and biodegradable and non-biodegradable substances (O'Melia, 1970). These substances affect the color, odor and taste of the water and may be harmful to humans. Ions, such as calcium and magnesium, contribute to the hardness of natural water. Metals such as arsenic, lead, zinc, iron and manganese, enter water sources through human activity and need to be removed. Inorganic substances found in water include sand, clay and silt. Organic compounds found in water include substances and compounds such as humic and fulvic substances, products of protein degradation, pesticides, polychlorinated biphenyls (PCBs), industrial solvents and byproducts of industrial processes (CWWA, 1993).

In addition to inorganic and organic compounds, living organisms such as bacteria, viruses and parasites are found in water. Bacteria, such as *Salmonella, E. coli* and *Mycobacterium,* contribute to serious diseases in humans. Viruses that are of concern in water treatment are enteric viruses such as hepatitis A, rotaviruses and adenoviruses (AWWA, 1990). Another serious concern for water treatment facilities is parasites, such as *Giardia* and *Cryptosporidium,* which can result in serious cases of diarrhea and dysentery in humans (CWWA, 1993). In May 2001, a malfunctioning

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filtration system in North Battleford, Saskatchewan, resulted in the death of three people and more than 100 confirmed cases of illness due to *Cryptosporidium* in the drinking water (Edmonton Journal, 2001). The Saskatchewan incident is yet another reminder of the importance of very tight quality control in the operation of water treatment plants. The concern over the removal of parasites such as *Cryptosporidium* and *Giardia*, which are resistant to chlorine disinfection, has resulted in water treatment plants continually modifying their processes to ensure safe water. To treat incoming water, plants use a combination of coagulation, flocculation and sedimentation to remove most of the particles from the water. Any remaining particles are removed in a filtration stage. The filters are the final particle removal step in the water treatment process so it is essential that any remaining particles are captured there. To improve filtration efficiency, water treatment plants have employed filter aid polymers which assist with the aggregation of particles.

Filter aid polymers change the surface properties and apparent particle size in the water through some combination of charge neutralization and interparticle bridging. For a polymer to be effective, it must be completely dispersed into the water. Normally, very rapid and turbulent mixing is used to disperse the polymer as the addition of the polymer occurs shortly before the filters. Therefore, it is important that the mixing conditions be optimized to counteract the short time span available for mixing the polymer before it enters the filter.

To optimize the polymer dispersion, the fundamentals of mixing and the effects of surface properties must be understood. Mixing transfers energy into the system to break apart polymer drops and provide more surface area for molecular

diffusion. Solute properties, such as viscosity and surface tension, work against the mixing to keep the polymer from breaking apart. Another important property is the miscibility of the polymer in water, which can be evaluated by determining the cloud point curve and dispersion kinetics. All of these properties together have a direct effect on the success of polymer dispersion.

Most of the research done for this study on filter aid polymers was conducted on a pilot plant scale as it was not practical to conduct this degree of testing on the full scale plant. To be able to use the results from the pilot plant they must be transferable to full scale. This is achieved through the use of scale up parameters. Several different scaling parameters can be used in mixing including the average energy dissipation and energy dissipation at the impeller. The water treatment industry normally uses the scaling parameter G which is termed the root mean square velocity gradient. However, this approach was originally developed based on laminar flow conditions. When using any scale up parameter it is important to use the appropriate parameter for the application as some scaling parameters require specific conditions to be maintained such as geometric or dynamic similarity.

With the increased interest in the use of filter aid polymers to improve the filter performance with respect to particle capture, understanding both the mechanism of particle capture and the factors determining the optimum polymer dosage become the central issues. Previous studies have demonstrated the importance of mixing using anecdotal evidence. This study uses carefully controlled mixing conditions to isolate the mechanisms involved in particle capture and polymer dispersion. There are several factors that can affect the dispersion of the polymer including mixing

intensity and surface properties. All of these factors must be taken into consideration when determining the type and dosage of filter aid polymer and the mixing conditions to be used in the process.

1.1 Literature Review

To fully understand the use of filter aid polymers in water treatment, a general overview of coagulation and flocculation processes relating to the use of filter aid polymers is required. This overview requires consideration of the mixing vessels, filters and water-polymer properties. First, a summary of the coagulation and flocculation processes is presented including discussions about colloids and their stability, and the concepts of destabilization and aggregation. Next, the characteristics of filter aid polymers and their influence on coagulation and flocculation of colloid particles are presented. Specific factors that directly affect the coagulation and flocculation processes are also discussed. Mixing of the filter aid polymer is important to the processes of coagulation and flocculation, therefore, the mechanisms of laminar and turbulent mixing are presented. To understand turbulent mixing in depth, the concepts of time and length scales and the turbulent energy cascade are discussed. In analyzing the results for the mixing of the filter aid polymer, dimensional analysis and correlations were used and the basic concepts are presented in this section. Next, the theory of porous media filtration is summarized with discussions about the relevant mechanisms. The role of chlorine disinfection on particles is briefly discussed and the final section focuses on the surface properties of the polymer and their importance in the dispersion process.

1.2 Coagulation and Flocculation

Two important concepts needed in understanding the coagulation process are colloids and colloidal stability. A colloid has a size in the range from one nanometer to one micron. Colloids have a large specific surface area and tend to adsorb substances from the surrounding water. They can be classified as hydrophilic or hydrophobic depending on their affinity for water (Hammer and Hammer, 1996). Hydrophobic colloids are unstable. They are not thermodynamically stable but can be kinetically stable. These colloids, if given sufficient time, will settle out of the water. Hydrophilic colloids are thermodynamically stable in water and will aggregate only if solvency conditions are altered. In water treatment, the main objective is to destabilize colloids so that aggregation will occur and settling time will be reduced.

The term stability when applied to colloids refers to the ability of individual particles to maintain a dispersed state (Bratby, 1980). In water, the stability of a colloid is due to the interfacial forces between colloids and the water which arise from surface charges at the interface and hydration of surface layers of the colloid. The surface charges keep the colloids dispersed in the liquid. Surface charges originate in a colloidal dispersion in three different ways: (1) the surface charge is a result of chemical reactions that occur at the surface, (2) the surface charge results from lattice imperfections at a solid surface or (3) the surface charge results from the adsorption of ions.

At the interface of a colloid and a liquid there also exists an electrical potential (Akers, 1987). This electrical potential results in ions of like charge being repelled and ions of opposite charge being attracted to the interface. This potential around the

surface will vary with increasing distance from the surface as the potential depends upon the competition between the thermal diffusion of ions moving randomly and the attractive effect exerted by the surface charge.

According to Probstein (1989), there is a region near the charged surface in which an excess of counterions exists. These ions are distributed in a diffuse manner and work to neutralize the surface charge. This region is termed the electric double layer. Stern (1924) proposed that the electric double layer has two parts: a fixed inner layer of ions and an outer diffuse layer. Both layers contain positively and negatively charged ions, however, there will be a greater number of negative ions than positive ions if the surface charge is negative (Reynolds and Richards, 1991). In water treatment, the electrical double layer consists of an inner region that includes water molecules and adsorbed hydrogen and an outer diffuse layer that contains a distribution of ions. At the interface of the two layers, the electrical potential is the effective potential exhibited by the particle and is equal to the zeta potential (Akers, 1987). Zeta potential is the potential at the shear surface between the charged surface and surrounding liquid (Probstein, 1989). The shear surface that surrounds the particle encloses the volume of water that moves with the particles and includes both the fixed and diffuse layers around the particle. The zeta potential is related to the stability of the colloidal suspension: the greater the zeta potential, the more stable the colloidal suspension (Reynolds and Richards, 1991). Zeta potential measurements are useful in determining colloidal stability, in ion adsorption studies and in the characterization of particle surfaces.

Colloidal stability must be overcome so that particles can aggregate. This process of destabilizing particles in a given suspension is called coagulation (Hammer and Hammer, 1996). There are three methods by which particles are destabilized. The first method is the reduction of the zeta potential to a degree where the attractive van der Waals forces cause particles to aggregate when agitated (Reynolds and Richards, 1991). The second method is destabilization by enmeshment of particles in a precipitate as it forms. The third method is the destabilization of particles by the interparticle bridging between reactive groups on the colloids (Reynolds and Richards, 1991). This method usually results in the simultaneous destabilization and aggregation of particles and occurs only when polymers are used as destabilizing agents.

Once a particle is destabilized, mixing is used to bring particles in contact with one another so that aggregation can occur (Bratby, 1980). This is the flocculation process. The rate of aggregation is determined by the rate and efficiency of interparticle collisions. Collisions of particles occur by three transport processes: Brownian diffusion, fluid shear and differential settling. Brownian diffusion is due to the thermal energy of the fluid. Fluid shear arises from the velocity gradients which are induced in the liquid by passage around baffles or mechanical agitation, by flow through interstices in a granular bed or by sedimentation within a basin. Differential settling is the vertical transport of particles which results in collisions (AWWA, 1990).

The processes of destabilization and aggregation are brought about by the addition of chemicals or polymers to the water. Chemicals such as alum are used in

the first stages of the water treatment to remove a significant amount of particles. However, in treatment of the water prior to the filtration stage, polymers are normally used to achieve these objectives.

1.3 Polymers as Filter Aids

Filter aid polymers are added prior to the filtration stage to coagulate and flocculate suspended particles. These polymers may both increase the size of the particles entering the filter and increase the filters ability to capture particles. Since the polymers increase particle capture in the filters, they reduce the passage of life forms such as protozoan cysts that are not inactivated by disinfection.

Polyelectrolyte polymers are the most common type of filter aid polymers. These polymers are usually synthetic organic compounds of high molecular weight with a monomeric unit that contains an ionizable group such as a carboxyl, amino or sulfonic group. Depending on the type of ionizable group, the polyelectrolyte may be cationic (positively charged), anionic (negatively charged) or ampholytic (contain both positive and negative groups) (AWWA, 1990). Nonionic polymers contain no ionizable groups. The charge on the polymer determines the type of destabilization and aggregation that will occur. Cationic polyelectrolyte polymers function as destabilizing agents by bridge formation, charge neutralization or both (AWWA, 1990). Polymer bridging can occur by the bridging of two or more particles to one polymer molecule or by the interaction of the polymer chains adsorbed on to different particles. Charge neutralization occurs when an oppositely charged polymer is adsorbed onto the particle by electrostatic or chemical attraction and neutralizes the

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charge on the particle (Sato and Ruch, 1980). Anionic and nonionic polymers bridge across the diffuse layers which surround charged particles.

In addition to the charge on the polymer, the molecular weight and degree of branching of the polymer also affect its ability for aggregation. Polyelectrolytes are able to aggregate colloidal particles by adsorbing to the particles through the bonding mechanism between the functional group in the polymer and the site on the colloidal particle (Faust and Aly, 1983). Molecules that contain large numbers of binding hydrogen result in stronger bonds to both the filter media and colloids, making the removal of polymer from the filter media more difficult. Higher molecular weight polymers are more effective at collecting colloids as there is more active polymer segments available for attachment. The polymer molecules may attach to the filter media and extend across the pore. This may result in the direct flocculation of inactivated and living organisms in the water (Schwoyer, 1981).

The use of polyelectrolytes as filter aid polymers has resulted in increased filter run times. This increase is due to the higher flow rates that can be achieved because the polyelectrolytes strengthen the bond between the aggregates and the filter media. The increased flow rate carries aggregates deeper into the filter bed and permits a higher headloss to develop before aggregate migration into the filter effluent becomes a problem (Schwoyer, 1981).

When using polymers as filter aids, the pH level of the water, polymer dosage and agitation rate all affect the coagulation and flocculation processes. The pH level can significantly affect the flocculation process. It affects the nature and concentration of the charge present on the solid surface and it affects the intensity of the charge

present on the polymer chain. If the pH of the water causes the surface charges on the particle to increase, it may inhibit the collisions which are necessary to form aggregates, reducing the collision efficiency.

According to Akers (1987), the optimum dosage of polymer used for coagulation is proportional to the solid surface area. Coagulation will improve up to the optimum dosage but any increase past this point will result in reduced effectiveness. When the polymers are used in high concentrations, the degree of coagulation decreases and a point will be reached where the particles are completely restabilized by an adsorbed protective layer (Akers, 1987). At low polymer concentrations, the probability of polymer-particle collisions occurring is less resulting in fewer particles being destabilized. Therefore, to optimize the coagulation process, it is important to determine the optimal polymer dosage.

Agitation disperses the polymer and increases the contact between the polymer and surface of the particle. Insufficient agitation results in the coagulant being adsorbed in excess on some solid surfaces, leaving others uncovered. Agitation increases the rate of flocculation by increasing the rate of collisions. In addition to increasing the particle collision rate, vigorous agitation drives turbulent shear forces that cause large aggregates to break apart resulting in a smaller average aggregate size (Akers, 1987). This process of continual aggregation and break up will eventually lead to a steady state distribution of aggregate sizes (AWWA, 1990). For the formation of aggregates of a specific size, it is important to understand the effect of mixing on coagulation and flocculation processes.

1.4 Mixing

Stirred tanks are frequently used for liquid-liquid blending and for blending of miscible fluids. The geometry of the vessel and impeller determines the circulation pattern in vessel, which contributes to the overall mixing of the tank volume. Geometry includes the vessel shape and diameter, baffle width and height, impeller diameter and off-bottom clearance. Mixing vessels can be cylindrical or square in shape with flat or dished bottoms (Tatterson, 1991). The diameter of the mixing vessel, T, can range from 0.1 m for lab scale to 10 m or more for process scale. The liquid height in the vessel, H, can range from 0.3T to 1.2T for a single impeller configuration.

Baffles are placed in vessels to improve top to bottom circulation and prevent gross vortexing. The usual baffle configuration is four rectangular baffles with a width of T/12 or T/10 evenly spaced around the periphery of the vessel. The height of the baffles can be as high as, or shorter than, the liquid height in the vessel (Harnby *et al.*, 1992). The baffles are normally mounted on the wall, however, they may be mounted so that a small clearance is left between the baffle and the wall. Baffles are not required in square mixing tanks as the corners of the tank act to provide vertical circulation.

The impeller diameter, D, can range from T/4 to T/2. Impellers are mounted on the end of a shaft and are usually centered in the axis. When the impeller is mounted in the tank, the typical range for the off-bottom clearance, C, is from T/2 to T/12 (Tatterson, 1991). The off-bottom clearance also affects the circulation pattern in the tank.

The tank and impeller geometry and the rotational speed of the impeller determine the fluid flow pattern in a stirred tank. Radial impellers discharge fluid radially such that one circulation loop occurs above the impeller and another occurs below the impeller as illustrated in Figure 1.1a. Radial impellers include Rushton turbines, curved bladed disc turbines, flat bladed turbines with two, four or six blades and, to a lesser extent, paddles as shown in Figure 1.2. Axial impellers produce a single loop flow pattern as illustrated in Figure 1.1b. Axial impellers include marine propellers, pitched blade turbines and hydrofoils as shown in Figure 1.3. Pitched blade impellers can be used to pump fluid downwards or upwards. The geometry of hydrofoil impellers minimizes the formation of blade bound vortices and increases the axial pumping efficiency of the impeller. With the variety of impellers available, it is important to know the flow pattern each creates so the best impeller is used.

The rotational speed of the impeller determines the flow regime under which the system operates. The three flow regimes, laminar, transitional and turbulent, are delineated by the Reynolds number. The Reynolds number is the ratio of inertial forces to viscous forces. In laminar flow, viscous forces dominate while inertial forces dominate in turbulent flow. For a stirred tank, the Reynolds number is defined as:

$$Re = \frac{\rho ND^2}{\mu} = \frac{ND^2}{\nu} \tag{1}$$

where D is the impeller diameter and N is the rotational speed in revolutions per second (Uhl and Gray, 1966). For a stirred tank, the steady laminar flow regime occurs below a Reynolds number of 10. The fully turbulent flow regime is defined by

a Reynolds number greater than 2×10^4. The transitional flow regime is located between the laminar and fully turbulent regimes, $10 < \text{Re} < 2 \times 10^4$.

Once the flow regime is determined, the type of mixing can be evaluated. In general, the objective of mixing is to obtain submicroscopic homogeneity where molecules are uniformly distributed over a field (Uhl and Gray, 1966). If no mechanical mixing occurred, molecular diffusion would be the only available mixing mechanism and mixing times would be very long. To speed up this process, mechanical agitation is used.

In laminar mixing, the velocity gradients at the surface of the rotating impeller cause the fluid to be stretched and folded. This process of continual stretching and folding results in an increase in surface area which leads to an increase in the rate of molecular diffusion. The dominant force in laminar mixing is viscosity and the momentum imparted by the impeller is quick to die out. Laminar mixing is difficult and should be avoided if possible (Uhl and Gray, 1966).

Mixing under laminar conditions involves the continual stretching and folding of liquids where as turbulent mixing involves breaking apart clumps of fluid to increase the rate of molecular diffusion. Turbulent mixing occurs in three stages simultaneously but at different scales. The first stage of turbulent mixing is bulk dispersion which is the overall convection of the fluid due to large scales of motion. This causes the overall dispersion of fluid in the tank and is the initial step in the mixing process (Ulbrecht and Patterson, 1985). The second stage of turbulent mixing is where turbulent eddies reduce the size of large lumps of fluid. The energy imparted into the fluid by the impeller circulates the fluid throughout the tank and back to the

impeller. As the fluid circulates it encounters a spectrum of turbulent eddies. The random motion of these turbulent eddies breaks apart unmixed clumps of pure components reducing them in size. Larger turbulent eddies convect elements of fluid away from the initial source. Although these turbulent eddies reduce the size of fluid clumps, they can not mix the fluid down to the a molecular scale. The reduction in size will continue until a size is reached where turbulence is no longer effective. Once this size is reached, molecular diffusion becomes the controlling mechanism and the third stage of mixing.

In stirred tanks, the most intense turbulence occurs at the impeller. The impeller region is the area where energy enters the tank and strong trailing vortices are formed at the tip of the impeller blades. The Rushton turbine impeller forms two vortices on each blade, one along the top and one along the bottom. For propellers and PBTs, a single weaker vortex is formed at the tip of each blade. According to Oldshue (1989), the volume of the vortices is about 5% of the total tank volume. To achieve good mixing, the fluid must pass through the impeller zone.

The previous section discussed turbulent mixing and the impact of turbulent eddies on the mixing. To characterize these turbulent eddies, time and length scales are used. These scales are used as reference points for the spectrum of sizes in turbulence. For mixing applications, some of the available time scales include the circulation time, the residence time in the tank, blend time and micro-time scales such as the Batchelor time scale. The Batchelor time scale is the time required to dissipate the energy contained in the smallest eddies. Small scale motions tend to have small

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time scales which are independent of the slow, large scale marcoinstabilities and mean flow.

Length scales can be interpreted as the variation in the size of turbulent eddies in the system. This variation in length scales can be thought of as a cascade of energy from the large scale eddies to progressively smaller scale eddies as illustrated in Figure 1.4. In turbulent mixing, energy is transferred from a mechanical source (i.e. impeller) to the process via turbulent eddies. Energy enters into the flow at the largest or integral scale of motion. Experimental evidence suggests that the size of the trailing vortices produced is of the order of the system size. The large eddies in the tank do most of the transport of momentum and contain the bulk of the kinetic energy. However, these flows are very unstable and the large scale eddies are quick to break up into smaller eddies (Harnby *et al.*, 1992). These smaller eddies represent a spectrum of eddies from the integral scale of motion down to the Kolmogorov scale. This range of eddies is where energy is passed between eddies with no dissipation and is termed the inertial subrange. As the eddies continue to decay and become smaller, a limit will be reached where the dissipation of energy into inertial energy is due only to molecular viscosity. This is the point where the smallest scales are found and is termed the Kolmogorov scale (Tatterson, 1991). At the Kolmogorov scale, viscous and inertial forces are in balance and are defined by the local Reynolds number being equal to one. The Kolmogorov length scales are the smallest scales occurring in the turbulent motion and these scales decrease with increasing dissipation rates. The Kolmogorov scale, η, defines the size of the smallest sustainable eddy:

$$\eta = \left(\frac{v^3}{\varepsilon}\right)^{1/4} \qquad (2)$$

where v is the kinematic viscosity and ε is the rate of energy dissipation per unit mass.

At a length scale of 5η, the viscous dissipation of energy becomes rapid and below this range, energy is dissipated by viscosity in the viscous sub-range.

The time and length scales and energy transfer that are found in a stirred tank can be expressed using dimensional analysis and mixing correlations. Dimensional analysis is used to produce dimensionless groups. These groups may be derived using the governing flow equation, such as Navier-Stokes, and the flow geometry such as tank diameter. Various stress, velocity and length scales are used to dimensionalize the governing flow equations. The flow geometry imposes its own dimensionless parameters such as diameter ratios (Masliyah *et al.*, 1996). The dimensionless groups that emerge from this process depend on the choice of scales. The choice of using a given set of dimensionless groups rests on the flow regime under consideration. For a more detailed discussion of the derivation of dimensionless groups refer to Masliyah *et al.* (1996).

In mixing of polymer in water treatment applications, the residence time in the tank and blend time are the two most important time scales. The blend time in the tank depends on the power input to the system. This power input leads to the transfer and dissipation of energy in the tank. The higher the rate of energy dissipation, the shorter the blend time in the tank. If the energy dissipation was not a contributing

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factor to the mixing, there would be no need for turbulent conditions as molecular diffusion would dominate.

The residence time in the tank represents the average time that a particle will be retained in the tank before it exits and is given by:

$$\tau = \frac{V}{Q} \tag{3}$$

where V is the volume of the tank and Q is the volumetric flow rate. This time scale is used in comparison with blend time when designing equipment as the particles must remain in the tank longer than the blend time to ensure that they will be mixed.

The blend time which is used in the design of mixing equipment represents the time required to completely mix the fluid in the tank. A study done by Grenville *et al.*(1995), developed a correlation for the blend time in the turbulent and transitional flow regimes in terms of the dimensionless quantities. The blend time correlation relates the properties of the impeller and the mixing in terms of the blend time. The blend time correlations for turbulent and transitional flow regimes, respectively, are:

$$\theta_B = \frac{5.2}{N Np^{1/3}} \left(\frac{T}{D}\right)^2 \qquad Re > \frac{6370}{Np^{1/3}} \tag{4}$$

$$\theta_B = \frac{33856}{N Np^{2/3} Re} \left(\frac{T}{D}\right)^2 \qquad 10 < Re < \frac{6370}{Np^{1/3}} \tag{5}$$

The blend times for both the transitional and turbulent flow conditions contain the power number, Np. Power input into the system is very important for characterizing

the performance of the impellers and is usually expressed as the power number. The power number is a function of the Reynolds number and is defined by:

$$Np = \frac{P}{\rho N^3 D^5} \tag{6}$$

where N is the rotational speed in revolutions per second, D is the impeller diameter and P is the input power.

In the laminar flow regime, the power number decreases linearly with the Reynolds number, but in the turbulent flow regime, the power number is constant. Fully turbulent power numbers for different impellers are given in Table 1.1. For power numbers throughout the turbulent, transitional and laminar flow regimes, Table 1.2 gives the appropriate equations.

An impeller with a low power number must be operated at higher speeds to achieve the same energy dissipation as an impeller with a high power number (Grenville *et al.*, 1995). The power number of the impellers can vary by a factor of 20 and when comparing equal power per unit mass and impeller to vessel diameters, impellers with low power numbers will rotate faster.

The blend time correlations for the turbulent and transitional regimes include both the tank and impeller diameters. A study done by Mao (1999) concluded that for square mixing vessels, the tank diameter should be equal to the diagonal of the tank as illustrated in Figure 1.5. The following formula is used to calculate this equivalent diameter

$$T = (L^2 + W^2)^{1/2} \tag{7}$$

where L in the length of the tank and W is the width of the tank. Since most tanks in water treatment applications are square, this is how the tank diameter was calculated.

The blend time in the tank can be used as a parameter to compare the performance of a turbulent impeller to a pumping impeller. When the blend time and the impeller diameter are held constant, the different impellers will require different rotational speed and power input to achieve the same blend time. This results in different levels of energy dissipation in the tank. The energy input into the tank is dissipated throughout the tank by turbulent eddies. Due to the variation between eddies, the energy is not dissipated equally through out the tank. Therefore, the average energy dissipation is expressed as the power per unit mass and is often used as a scaling parameter.

$$\varepsilon = \frac{P}{\rho V_{Tank}} \qquad (8)$$

The average turbulent energy dissipation can also be expressed in terms of geometric configuration and rotational speed as given by

$$\varepsilon = NpN^3 D^2 \left(\frac{D}{T} \right)^3 \qquad (9)$$

This scaling parameter introduces a factor of $(D/T)^3$ which works well if the bulk characteristics of the flow dominate. In mixing applications, the general scale up rule is to use $P/\rho V_{tank}$ as it is the simplest way to characterize the turbulence in the tank and is an estimate of the gross average dissipation. There has been limited success using this relationship as a scaling parameter provided that geometric similarity is maintained. Maintaining geometric similarity means that all dimensions and velocity

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scales will scale by the same factor. If geometric similarity is maintained, the levels of turbulent energy dissipation at the impeller and in the tank will remain the same provided that $P/\rho V_{tank}$ is held constant. However, the time scales over which individual fluid particles experience the various turbulence fields will change. This parameter is not an accurate measure of turbulence if local characteristics are needed. Therefore, the power per impeller swept volume is often used as an alternative scaling parameter. The power per impeller swept volume is defined as follows

$$\varepsilon_1 = \frac{P}{\rho V_I} \qquad (10)$$

where V_I is the impeller swept volume and is defined as

$$V_I = \frac{\pi}{4} D^2 h \qquad (11)$$

for simple impellers.

The energy dissipation at the impeller can also be expressed in terms of rotational speed and impeller configuration:

$$\varepsilon_1 = NpN^3 D^2 \qquad (12)$$

This parameter is the best order of magnitude estimate of the maximum energy dissipation in the tank. This parameter also has more of a physical significance as it is characterizing the turbulence around the impeller which contributes to the mixing. The $P/\rho V_I$ scaling parameter is more robust than $P/\rho V_{Tank}$ as it does not require geometric similarity to be maintained (Kresta, 1998). This is a better parameter to use in scaling down when full scale vessel dimensions cannot be duplicated on a small scale.

The scaling parameter used in water treatment is the mean shear rate, G. This parameter is widely used in the design of rapid mixing and flocculation facilities and is used to evaluate how the shear rate affects flocculation. Camp and Stein (1943) argued that the mean shear rate can be calculated from the power per unit volume

$$G = \left(\frac{P}{\mu V} \right)^{\frac{1}{2}} \tag{13}$$

where P is the power transferred from the impeller, μ is the dynamic viscosity, and V is the volume of the tank. Camp and Stein (1943) developed this parameter by considering the angular distortion of an elemental volume of water due to shear and assumed that the equation they developed for the absolute velocity gradient was valid for both viscous and turbulent flow. However, this is not correct as the basic relationship between shear, viscosity and velocity gradient that was used can not be used to describe a turbulent system. The main reason why this relationship can not be used is that viscous forces are negligible in turbulent conditions. Even though this scaling parameter is referred to as the mean shear, it does not specifically contain any information about shear rate. It actually contains the same information used to define the average energy dissipation in a stirred tank which used to describe the turbulence in the tank. The parameter G is based on the power imparted into the system, which leads to the creation of turbulence in the tank. The shear rate, G, can be related to the mean rate of energy dissipation through the following equation

$$G = \left(\frac{\bar{\bar{\varepsilon}}}{\nu} \right)^{\frac{1}{2}} \tag{14}$$

where $\bar{\varepsilon}$ is the average power dissipation and ν is the kinematic viscosity (Cleasby, 1984). Traditionally, it has been assumed that if G is held constant, the mixing environment is constant as well. According to Koh *et al.*, (1984), the approach of using a single G value to describe the system is correct only if the turbulence is homogeneous and isotropic. Comparing G to the average energy dissipation shows that if viscosity is constant, as is the case in water treatment, the parameter G is equivalent to using the average energy dissipation. This means that if geometric similarity is maintained that G can be used as a scale up parameter. Difficulties with using G arise when geometric similarity is not maintained or when the fluid is changed due to the inclusion of viscosity. All of these scaling parameters have applications where they have been successful in scaling and it is important when using these parameters to understand what they represent and how they apply to the mixing application of interest.

1.5 Theory of Porous Media Filtration

The previous section investigated turbulent mixing. However, mixing of the filter aid polymer is only one step in the process of particle removal. Filtration is required for the physical removal of particles from the water. It is the process where water is purified as it passes through porous media (Huisman, 1970). This process removes suspended solids and organisms from the water by attachment to the filter media.

The media in the filter may consist of an assortment of material including silica sand, anthracite coal, granular activated carbon and garnet. These media may be used alone or in dual or triple media combinations (AWWA, 1990). For water

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treatment, sand and dual media filters are normally used. The filters usually consist of one or more layers of particulate solids supported on a gravel bed on a grating through which the material being filtered can flow. Properties of the filter media such as size, shape, density, hardness and porosity affect the filter performance. Grain size has an important effect on the filtration efficiency and backwash requirements. A typical filter can contain particles whose size varies by a factor of at least two (Stevenson, 1997). The shape of the filter media affects the headloss, filtration efficiency and fixed bed porosity. The fixed bed porosity which is the ratio of void volume to total bed volume is directly affected by the media shape. Angular grains have a higher fixed bed porosity than spherical grains. Grains of media rest against each other in a random manner so the pore size between the grains can vary. The media density affects the backwash flow requirements as a higher density media requires higher wash rates to achieve fluidization. The hardness of the filter media is important for long-term service as the filter media must be durable to withstand the backwashing processes.

Single medium filters that use sand or anthracite coal require a deeper bed to achieve comparable removal of particles. In a single medium filter, the available pore volume for solids storage is in the top portion of the bed. Single media filters usually have a depth of 0.61 to 0.76 m (Reynolds and Richards, 1991). These filters require excessive wash rates to fluidize the medium so the medium is washed without fluidization by concurrent upflow of air and water (AWWA, 1990).

The main advantages of using dual or triple media filters over single media filters are higher filtration rates, longer filter run times and the ability to filter water

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with higher turbidity and suspended solids (Reynolds and Richards, 1991). This is due to media particle sizes, different specific gravities of the media and the media gradation. With multi-media filters, the available pore volume extends deep within the filter bed so that more particles penetrate deeper in the bed.

There are three mechanisms involved in the filtration process: transport, attachment and detachment. The transport mechanisms are the forces which act on a particle to move it across streamlines (Ives, 1975). These forces include interception, inertia, diffusion, gravity and hydrodynamic forces and are illustrated in Figure 1.6. Interception occurs when a particle passes along a streamline close enough to touch the media leading to attachment. Inertial forces which keep the particle from following the tortuous path of the streamline results in impaction with the filter media (Barnes and Wilson, 1983). Diffusion is the transport of particles by random motion and affects particles that are less than 1 μm in diameter. Gravity forces settle particles out of the liquid and are only effective on particles larger than 5 μm and with a density greater than water. Hydrodynamic forces are a result of the velocity distribution in the filter pores. Viscous drag forces cause the particle to rotate and translate across a flow field toward the filter media surface (Ives, 1975).

An attachment mechanism is required to retain the particles in the filter otherwise particles will flow through the filter. This mechanism involves electrostatic interactions, chemical bridging and specific adsorption. Particles in water have a small negative electric potential that may result in an electrical repulsion that keeps particles from attaching to the sand. However, attractive London-van der Waals

forces also exist between particles and grain surfaces. Attachment will only occur if the attractive forces are greater than the repulsive forces (Russel *et al.*, 1989). Chemical bridging results from the chemical bonding and bridging of suspended particles to the filter media. Adsorption is the mechanism by which particles from the water adsorb to the surface of the filter media.

The detachment mechanism is important after accumulated deposits have clogged the filter pores. When particles clog the filter bed, headloss development occurs in the filter unit (Vigneswaran and BenAim, 1985). As headloss increases, the effluent quality decreases and when this occurs the filter needs to be cleaned. To clean the filters, air scouring and backwashing techniques are used. Air scouring is the process where air is forced through the filter to remove particles from the sand and is usually done prior to backwash process. To backwash the filter, the water flow is reversed so the underside of the filter bed is exposed to water. This detaches the particles that accumulate in the filter pores and removes them.

The removal of suspended solids from water occurs by surface removal at the top of the filter bed and depth removal within the filter bed (Baumann and Oulman, 1970). When the water contains large aggregates, surface removal will be predominant as the top pores become rapidly clogged. Large aggregates settle on the top of the media creating a straining action that removes other incoming aggregates. When the water contains small aggregates, depth removal will dominate. Smaller aggregates are carried by the water into the filter and deposit in the openings between the media in the bed. Other aggregates collide with previously deposited aggregates resulting in the formation of large aggregates. The accumulated aggregates decrease

the effective pore spaces in the filter which results in increasing velocities through the pores. These increased velocities result in aggregates penetrating further into the filter bed (Zhu *et al.*, 1996). Regardless of the incoming aggregate size, the water quality at the beginning of a filter run is poor as the filter needs to be conditioned. As the number of particles deposited in the filter increases, the water quality increases. The water quality will increase until a breakthrough occurs which indicates that the filter can no longer capture particles and needs to be cleaned.

1.6 Effect of Chlorination

Chlorine is used in water treatment for control of tastes and odors, removal of color, iron and magnesium, prevention of algae growth and to clean filter media (Pierce, 1978). Aqueous chlorine is an effective and versatile chemical oxidant. Chlorine is used as a disinfectant of potable water because it is effective at low concentration and forms a residual if applied at a sufficient dosage. This residual works to disinfect the water in the distribution system ensuring safe water up to the consumer's tap (Reynolds and Richards, 1991).

When pure chlorine is added to water it rapidly dissociates and forms hypochlorous acid (HOCl).

$$Cl_2 + H_2O \longleftrightarrow HOCl + H^+ + Cl^- \qquad (15)$$
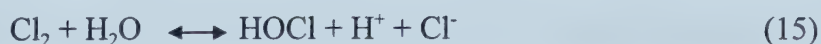
Hypochlorous acid is a weak acid and partially dissociates to hypochlorite ion (OCl^-).

$$HOCl \longleftrightarrow H^+ + OCl^- \qquad (16)$$
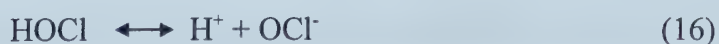
The amounts of the different chlorine species present in the water depend upon the total concentration of chlorine, the pH and the temperature of the water (AWWA, 1990). Hypochlorous acid is the predominant species in the pH range of 1 to 7. In a

dilute solution with a pH greater than 3, Equation 15 is displaced to the right resulting in very little molecular chlorine gas remaining dissolved and unreacted (Reynolds and Richards, 1991). At a pH of 7.5, chlorine, hypochlorous acid and hypochlorite ion are at equal concentrations. For a pH higher than 7.5, the predominant species is hypochlorite ion.

In addition to forming hypochlorous acid, chlorine reacts with substances in the water to form other chlorine derivatives with less desirable characteristics (Ingols, 1961). Chlorine also reacts with some reducing agents to take on a new identity with reduced disinfecting intensity (Ingols, 1961). Chlorine readily reacts with organic compounds such as nitrites, iodine, bromine, phenols, olefins and humic substances. Ammonia and amino nitrogen compounds will react with the chlorine to form compounds such as monochloramine, dichloramine and trichloramine (AWWA, 1990). Chlorine also reacts with ions such as Fe^{+2}, Mn^{+2} and NO_2^-.

The main purpose of chlorine addition in water treatment is to reduce the number of pathogenic microorganisms. When chlorine enters into the environment of a living organism, it undergoes several reactions with critical components which results in the inactivation of the organism. Chlorine oxidizes enzymes of the microbial cells which are essential for the cells' metabolic processes (Reynolds and Richard, 1991). It affects the respiratory transport of bacteria and disrupts the nucleic acid activity. The chlorine can destroy or impair cellular structural organization and interfere with growth and biosynthesis. The wall of the cell can be damaged or oxidized by the chlorine such that the wall ruptures or cellular disintegration occurs (CWWA, 1993). Chlorine also affects the surface properties of organisms. An

example of this is inactivation of the polio virus through chlorine "attack" on its the protein coating (AWWA, 1990).

Not all microorganisms in the water can be inactivated by chlorine: some microorganisms can protect themselves. These microorganisms may adsorb or be enmeshed into nonviable solid particles in the water. Some microorganisms can convert to a cyst or resistant form during inactivation. Genetic variants may exist in the population that are resistant to disinfection. The organisms may clump together making it difficult to inactivate individual organisms.

1.7 Surface Properties

When using polymers as filter aids, it is important to understand the impact that surface properties have on their ability to be dispersed. Physical properties of a fluid, such as viscosity and surface tension, determine the ease with which it will flow, be mixed into solution or broken apart under shear forces. The solubility and miscibility of the polymer are also important in understanding the dispersion of the filter aid. To investigate the solubility, the temperature at which a polymer solvent system exists in separate phases, or cloud point, is beneficial in determining if the polymer is useful at operating temperatures. The miscibility of the polymer dictates the time required to achieve homogeneous conditions.

The viscosity of the polymer solution provides information on the mixing time required to achieve homogeneous conditions and on the conformational behavior of the polymer in solution. The viscosity of the polymer solution can be used to determine the intrinsic viscosity which is a direct measurement of the hydrodynamic volume of an isolated polymer molecule in the environment (Molyneux, 1983). The

inverse of the intrinsic viscosity is used to determine the critical overlap concentration. The critical overlap concentration is the point where polymer chains in solution overlap and are densely packed in solution. At concentrations below the critical overlap concentration, the polymer coils begin to interact with each other and have started to interpenetrate or overlap. The solution in which this is seen is termed a semi-dilute solution. In a dilute solution, where the polymer concentration is low, the polymer chain coils exist separately in solution. At this concentration, there is very little interaction between the polymer coils in solution. The configuration of the polymer in solution can have an effect on the mixing processes.

Surface tension is a property of the interface between two phases and determines if a drop will break apart into smaller drops or if a liquid will remain stationary when contacted with a solid surface (Probstein, 1989). Surface tension is a force that operates on a surface and acts perpendicular and inward from the boundary of the surface. Surface tension is a bulk property that is due to intermolecular interactions that are short range in macroscopic terms. These intermolecular interactions include hydrogen bonding, permanent dipole interactions and London forces. In hydrogen bonding, hydrogen atoms serve as bridges linking together two atoms of high electronegativity. With permanent dipole interaction, the regions of opposite charge on different molecules result in an attraction between molecules (Hiemenz and Rajagopalan, 1997). London forces are due to the deforming electron clouds in adjoining molecules that distort one another. This results in the instantaneous polarity and the accompanying attraction between molecules. London forces attract all molecules together regardless of their chemical nature however, the

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other intermolecular interactions are more specific and only operate in systems the possess the requisite special features. Therefore, surface tension is best illustrated by considering the specific surfaces that are involved.

For colloidal systems, surface tension will keep particles together after a collision. According to Probstein (1989), molecular motion and random currents in a liquid will bring about collisions between small particles in suspension and surface tension tends to cause coalescence of fine particles. This leads to particle size growth in the liquid. The degree of surface activity of a material depends on surface adsorption and its mixing in the aqueous phase. However, for two immiscible liquids, there is an interfacial tension acting at the liquid-liquid interface, the magnitude of which lies between the surface tensions of the two liquids. It is this interfacial tension that opposes the break up of the liquid drops.

Surface tension is not the only property that effects the dispersion of the filter aid polymer. Another important property to consider is the solubility of the polymer in water. To evaluate the solubility of a polymer-water system at equilibrium, the cloud point of the system can be used. According to Flory (1952), if the solvent of a polymer-solvent system becomes progressively poorer as the temperature of the solution is lowered, eventually a temperature will be reached where the polymer and solvent are no longer miscible. It is more favorable to separate into two phases, one polymer rich and the other polymer poor. The point at which this occurs is known as the cloud point temperature. At each temperature lower than the cloud point temperature, the mixture of polymer and solvent will separate into two phases. In the vicinity of the cloud point, a slight increase in temperature will affect the phase

volumes by increasing the polymer rich phase. This increase is due to the worsening of the solubility (Joabsson et al., 1998). The maximum temperature for the co-existence of two phases in the system formed from a given polymer and solvent is not in general a true critical point and depends on the distribution of species in the solution (Flory, 1952). The cloud point temperature is a function of the molecular weight and is weakly dependent on the concentration of the solution (Shinoda et al.,1963).

Shinoda et al. (1963) reported that for aqueous solutions of commercial nonionic polymers there exists a double cloud point. This means that the solution will become turbid at the first cloud point, then as the temperature is increased, the solution will become less turbid. As the temperature is increased more, the solution will again become turbid and eventually separate into two phases.

One method used to study the phase behavior of polymer-solvent systems is to evaluate the cloud point curve. This is achieved using a set of samples with different compositions and altering the temperature to induce phase separation. The cloud point is indicated when the solution becomes turbid (Joabsson et al., 1998). The shape and position of the cloud point curve depends on the molecular weight of the polymer. Figure 1.7 shows an example of a cloud point curve for a surfactant water system that is heated then cooled.

The mechanism of the cloud point phenomenon is not clearly defined but several mechanisms have been proposed. Shinoda et al. (1963) proposed that the micellar weight of a nonionic surfactant becomes larger as the temperature of the solution is increased. If this tendency persists with increasing temperatures, then the

micelle growth becomes large enough that the turbidity of the solution become detectable. Gu and Galera-Gomez (1995) suggested that the clouding that is seen as the solution progresses from a homogeneous state to a heterogeneous state is caused by a change in the balance of the hydrophilic and hydrophobic interactions. According to Nilsson *et al.* (1998) in a study done on ethylene oxide based surfactant water system, the mechanism for the phase separation was due to changes that make the head group region of the surfactant more hydrophobic resulting in the phase separation.

The cloud point is used to define the solubility of a liquid-liquid system at equilibrium, though it does not define the miscibility of the liquid-liquid system. However, when referring to a liquid-liquid system, it is important to distinguish between a solution and a dispersion. In a solution, a solute is dissolved into the solvent where as in a dispersion, one liquid is interdispersed in another liquid. This concept can be illustrated by using a solid-liquid system to visualize what occurs. An example of a solution is when sugar is dissolved into water. The sugar seems to "melt" into the water and there is no clearly defined interface. An example that can be used to visualize a dispersion is the suspension of solids in an liquid. In the suspension, the solids particles are interdispersed in the liquid, much like a liquid would be in a dispersion, and a clearly defined interface can be seen. Liquid-liquid systems that form a solution are termed as miscible and liquid-liquid systems that form a dispersion are termed immiscible.

Mixing two miscible liquids requires that the inertial forces generated by the agitator overcome the viscous and buoyancy forces of the liquids. When the two

liquids have similar viscosities, homogeneous conditions can be reached in a short time. An example of mixing miscible liquids of similar viscosities is mixing dye into water which requires very little time and energy input to achieve homogeneous conditions. If there is a significant difference in viscosity between the liquids, there will be additional resistance to the break up of the more viscous liquid drops, which leads to longer mixing times (Bouwmans *et al.*, 1997). However, the initial difference will be reduced with time and all parts of the liquid will approach the same concentration (Uhl and Gray, 1966). Even though mixing miscible liquids of differing fluid properties requires longer mixing times, these mixing times are still relatively short when compared to the time required to achieve homogeneous conditions when mixing immiscible liquids. Dispersion of two immiscible liquids may require considerable mixing times to reach equilibrium drop distribution.

The interdispersion of immiscible liquids is a result of continuous break up and coalescence of drops which is brought about by fluid dynamic forces that overcome surface tension. Drops are broken up by turbulent pressure fluctuations (inertial forces) and viscous shear forces that are created by velocity gradients in the surrounding continuous phase (Zhou and Kresta, 1998a). When drops are larger than the microscale of turbulence, viscous force are negligible and inertial forces dominate. If surface tension is very small, the drop size will be smaller than the scale of turbulence and viscous shear forces will dominate (Rase, 1977).

In the process of drop break up there is a combination of deforming and reforming stresses working against each other. Inertial and viscous shear forces deform and stretch a drop and the elastic stresses generated by surface tension will

restore a drop to its original shape and resist dispersion by attempting to retain drop sphericity and prevent gross distortion that leads to break up (Calderbank, 1967). As the diameter of the drop decreases, the deforming stresses across it will decrease while the restoring stresses will increase (Zhou and Kresta, 1998a). The drop diameter will decrease to a certain size below which further breakage is unlikely as the deforming stresses are unable to break the drop. This diameter is the maximum stable drop diameter and is encountered in the impeller zone of an agitated tank where the maximum deforming forces are found. Drop break up occurs as the drop flows over the blade or in the vortex system of the impeller blade. As a drop flows over the blade, very small drops can be formed by a bursting mechanism because of a high pressure drop between the front and back of the impeller.

The coalescence of drops occurs at the impeller where the collision energy is highest. The main drop break up and coalescence in the tank occur at the impeller at intervals defined by mean circulation time (Kresta, 1998). A dynamic equilibrium will be established between drop break up and coalescence which creates a spectrum of drop sizes. However, reaching this equilibrium state requires a significant amount of time. Interactions between the mean circulation time and the level of turbulence at the impeller determine the mean drop size, shape of the final distribution and the rate of drop break up and coalescence (Zhou and Kresta, 1998b).

1.8 Rossdale Water Treatment Plant

The research for this study was conducted at a pilot plant located at the Rossdale Water Treatment plant. The plant is located in Edmonton, Alberta, Canada and treats

an average of 55,000 ML/year. Figure 1.8 shows a simple schematic of the processes that Rossdale Water Treatment Plant uses.

The water for the plant comes from the North Saskatchewan River. Low lift pumps are used to pump the water up from the river into the plant. The low lift pumps are 1000 horsepower pumps that can pump at a rate of 20 to 200 ML/day. Screens are located before the low lift pumps to strain out debris such as fish, sticks and leaves (Epcor website, 2001).

Once the water is pumped into the plant, alum is added and rapidly mixed to disperse it. This is the initial particle removal for the plant. As the alum is mixed into the water, it forms aggregates which interact with particles in the water. The water containing the newly formed aggregates flows into the clarifier basin where these aggregates are allowed to settle out by gravity. The aggregates settle on the bottom of the clarifier basin as a sludge which is removed by regular draining. The alum dosage for the plant varies between 20 mg/L to 200 mg/L, with the typical dosage being around 35 to 40 mg/L. The water spends about one to two hours in the clarification stage (Epcor website, 2001).

As aggregates settle to the bottom of the clarifier basin, clear water is decanted from the top. Chlorine is then added and mixed into the water to deactivate harmful bacteria and other microbes. After the chlorine addition, the water is sent to the stilling basin which provides contact time for the chlorine to react with the organisms.

After the water leaves the stilling basin, the filter aid polymer is added. The polymer is rapidly mixed to disperse it in the water before it enters the filters. The filters are quartz sand filters that remove any remaining particles from the water. The

filter aid polymer is thought to agglomerate the particles making them easier to capture in the filters. The filtration stage takes about one hour.

Once the water has passed through the filters, chemicals such as fluoride, ammonia and caustic soda are added. Fluoride is added to provide dental health and is added at a dosage of 0.8 mg/L. Ammonia is added to form the long lasting disinfectant monochloramine. This disinfectant deactivates bacteria in the water distribution system and keeps the water safe up to the customer's tap. Caustic soda is added to adjust the pH of the water to minimize corrosion and scaling problems in the distribution systems. Pipe corrosion occurs at pH levels lower than 6.5 and scaling increases at pH above 8.5. Therefore, the pH range for drinking water is kept between 6.5 and 8.5 (Epcor website, 2001).

After the chemical addition, the water is sent to the reservoirs which allow for more contact time for chemicals. The water remains in the reservoir for four to ten hours after which it is pumped to the consumer.

1.9 Problem Statement and Research Objectives

The Rossdale water treatment plant has been working towards increasing filter efficiency to enhance the removal of *Cryptosporidium* and *Giardia*. Previous studies conducted at the water plant have investigated the use of filter aid polymers which assist in the aggregation of particles in the water making them easier to capture in the filter. These studies evaluated the effect of polymer type, polymer dosage, and to a lesser extent, mixing intensity on the filtration process. The Rossdale water plant has found that dispersing the polymer prior to the filters results in longer filter runs times can be obtained than by adding the polymer directly to the filters. The more disperse

the polymer, the more surface area available for particle contact which results in more aggregate formation.   Therefore, it is beneficial to examine the dispersion kinetics of the polymer to determine the mixing requirements. A comparison of the dispersion kinetics with the available mixing times in the plant will assist in determining the proper filter aid polymer and conditions under which it can be effectively used.

The dispersion of filter aid polymers is affected by the properties of the polymer. Viscosity, solubility and miscibility of the polymer affect the mixing time. A large viscosity difference between the polymer and water will require a longer mixing time to achieve homogeneous conditions. The solubility of the polymer can affect the optimum mixing conditions for the polymer use. The solubility of the polymer determines the conditions under which the polymer will "dissolve" into solution.   A polymer may be water soluble but will require a long time to reach equilibrium.   However, if a polymer is soluble, it does not mean that the polymer is miscible.   Miscibility refers to the polymers ability to be dispersed in a solution, not dissolved.   If the polymer is completely miscible, it will mix easily into the water. However, if the polymer is immiscible, it will require long mixing times.   Therefore, to optimize the use of polymers in water treatment it is essential that both the solubility and miscibility be evaluated.

The main objective of this study was to determine the effect of different mixing conditions, with the addition of polymer, on the removal of fine particulates from drinking water. This study looked specifically at the effects of mixing on dispersion of the polymer.   The study attempted to determine if the dominant effect is micromixing at the impeller or bulk blending in the tank; and show the effect of

dispersion kinetics by changing the impeller from a turbulence dominated geometry to a convection dominated geometry. The study also attempted to define the dispersion kinetics of the polymer by using variable polymer concentrations and mixing intensities. The blend time, power per unit mass, shear rate and local dissipation at the impeller were examined by varying the impeller diameter, impeller geometry and agitation speed.

In addition to determining the effect of mixing, the surface properties of the polymer were investigated. The viscosity of the polymer was determined to understand its role on the dispersion process. The cloud point curve for the polymer was determined to examine the temperatures at which the polymer water system exists in a single phase. Finally, the interaction of chlorine with the polymer on filtration was briefly examined.

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Table 1.1. Power Numbers for Various Impellers in Turbulent Flow

Impeller	Power Number, Np
Rushton Turbine – Radial	5.0 – 6.0
Pitched Blade Turbine – 4 blades	1.3
A310 hydrofoil – Axial	0.3
Paddle with 4 blades – radial	3.1, 2.75*

* from Reynolds and Richards (1991).

Table 1.2. Equations for Power Number Curves for Selected Impellers (Pers. Corr. J. Smith, University of Surrey)

$$Np = \frac{A}{Re} + B + C\frac{Re}{(1000 + Re)}$$

Impeller	Blade Angle	# of blades	A	B	C
Rushton	90	6	67	3.2	1.8
Smith (RT with curved blades	90	6	67	2.6	2.2
PBT	45	4	49	1.5	0.3
PBT	60	4	50	4.0	1.0
Propeller	-	3	47	0.9	0.3
Paddle (no disk)	90	4	50	4.0	1.0
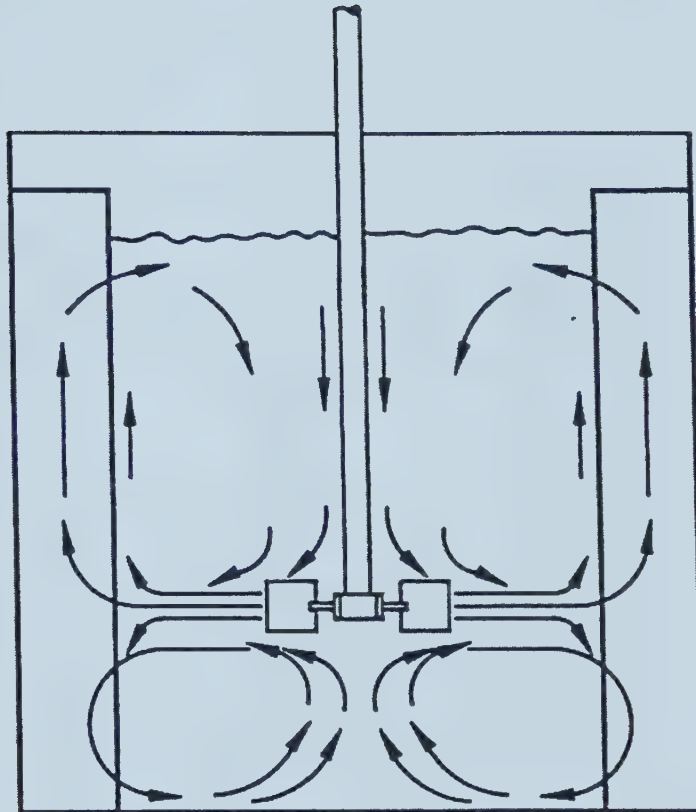
Figure 1.1a. General Flow Pattern for Radial Impellers (Godfrey and Amirtharajah, 1991. Copyright AwwaRF and AWWA. Reproduced with permission).
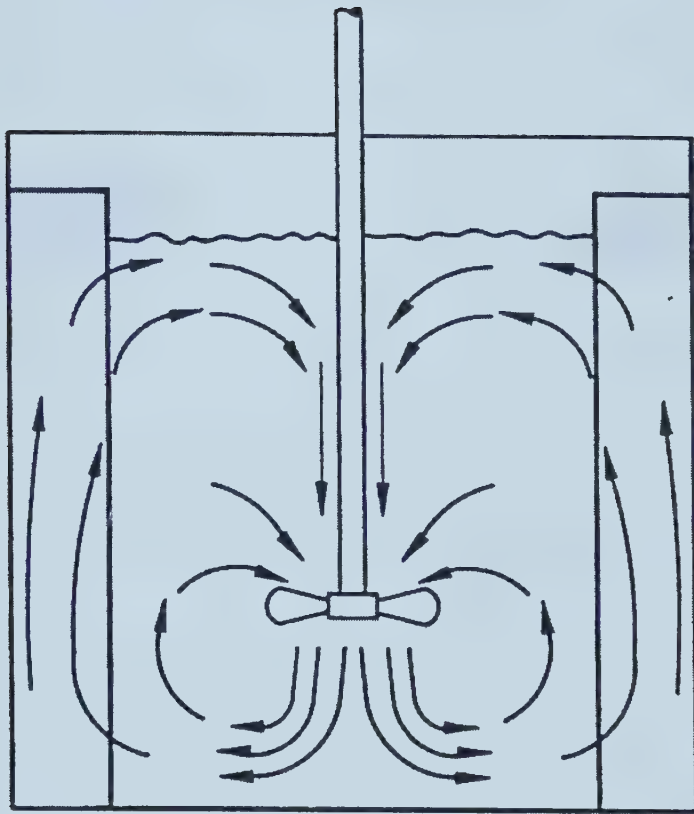
Figure 1.1b. General Flow Pattern for Axial Impellers (Godfrey and Amirtharajah, 1991. Copyright AwwaRF and AWWA. Reproduced with permission).
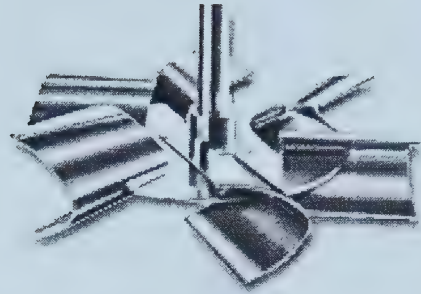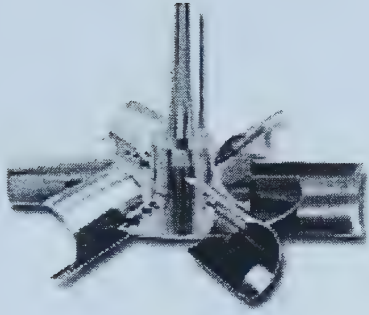
a) Curved Bladed Disc Turbines

b) Rushton Turbine
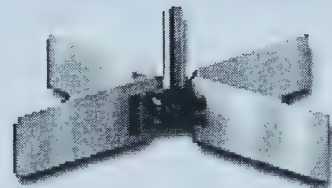
c) Paddle Impeller

Figure 1.2. Pictures of Radial Impellers (from Chemineer website)
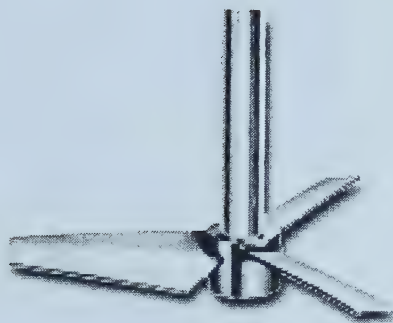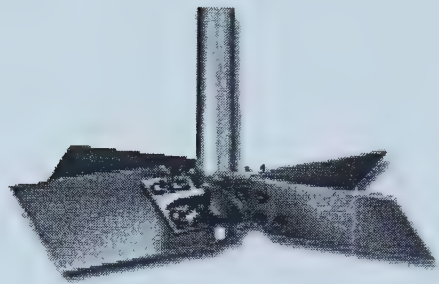
a) Marine Impeller   b) Pitched Blade Turbine
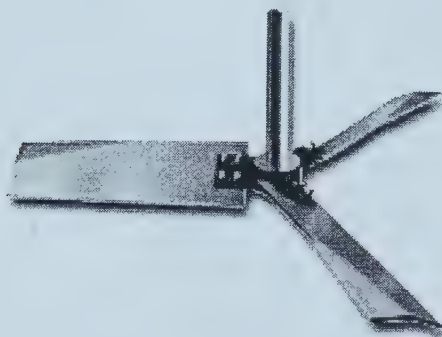
c) HE3 Impeller

Figure 1.3. Pictures of Axial Impellers (from Chemineer website)

Universal equilibrium range where turbulence is isotropic and has forgotten large scale motion

Inertial Subrange

Locally isotropic but not directly affected by viscosity

Anisotropic Inertial Transport

Dissipation (ε) effected by viscosity

Kinetic energy transport at rate ε by inertial interactions

Convection and Pressure fluctuations

Production

PARAMETERS GOVERNING SCALES

ε, ν

ε

$\varepsilon, \dfrac{\delta U}{\delta y}$

U_s, u_s, l

Figure 1.4. Idealized visualization of Turbulent Energy Cascade (modified from D. Wilson, University of Alberta)
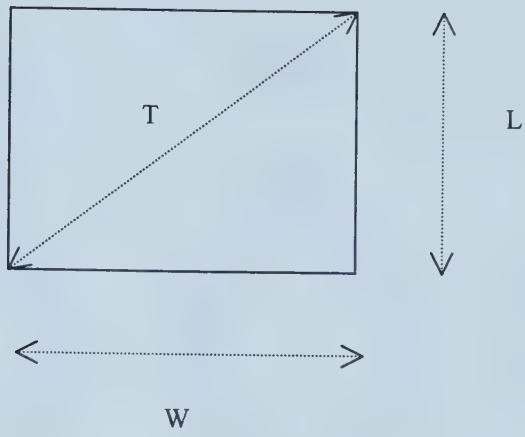
Figure 1.5. Illustration of Tank Diameter for Square Mixing Tanks
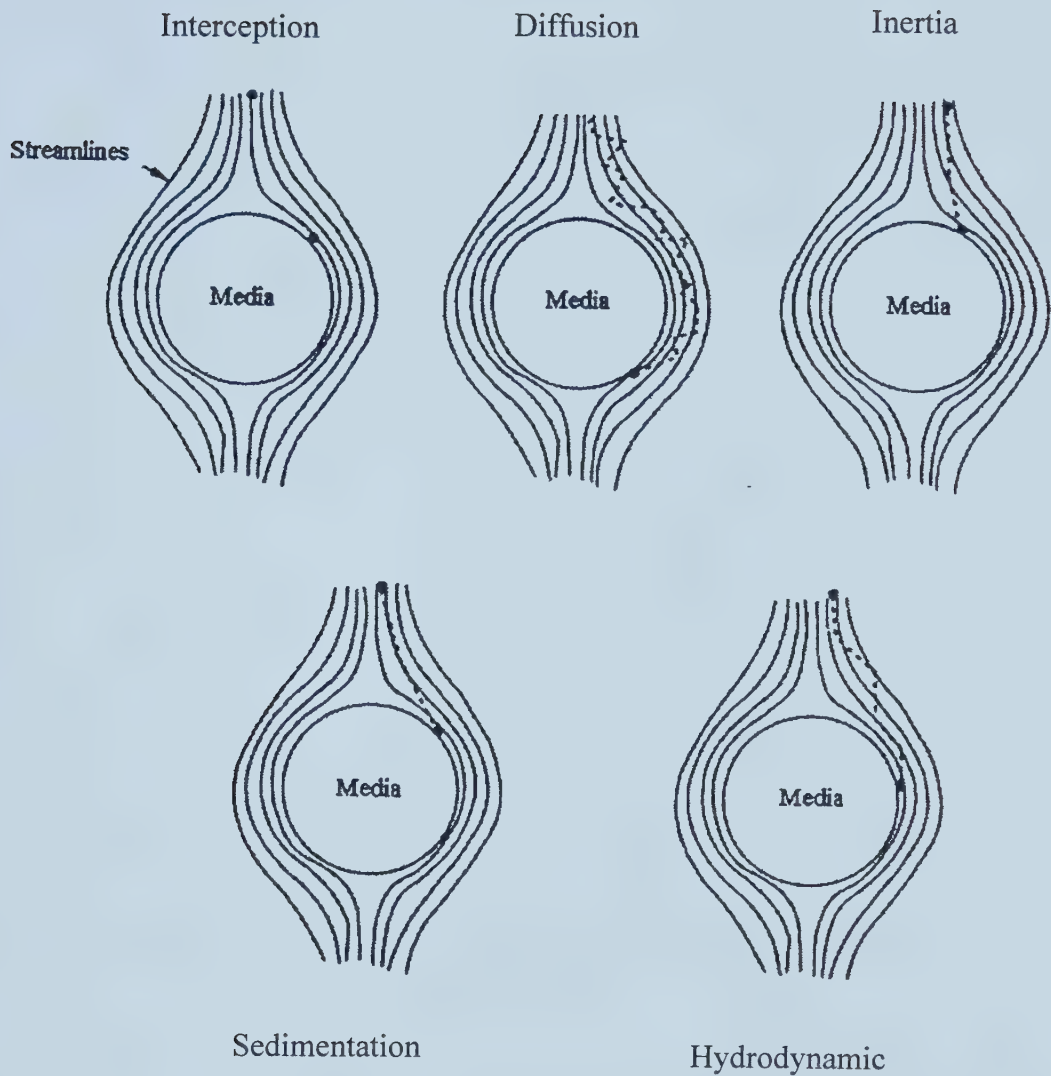
Figure 1.6. Transport Mechanisms in Filtration (modified from McEwen, 1998. Copyright AwwaRF and AWWA. Reproduced with permission).
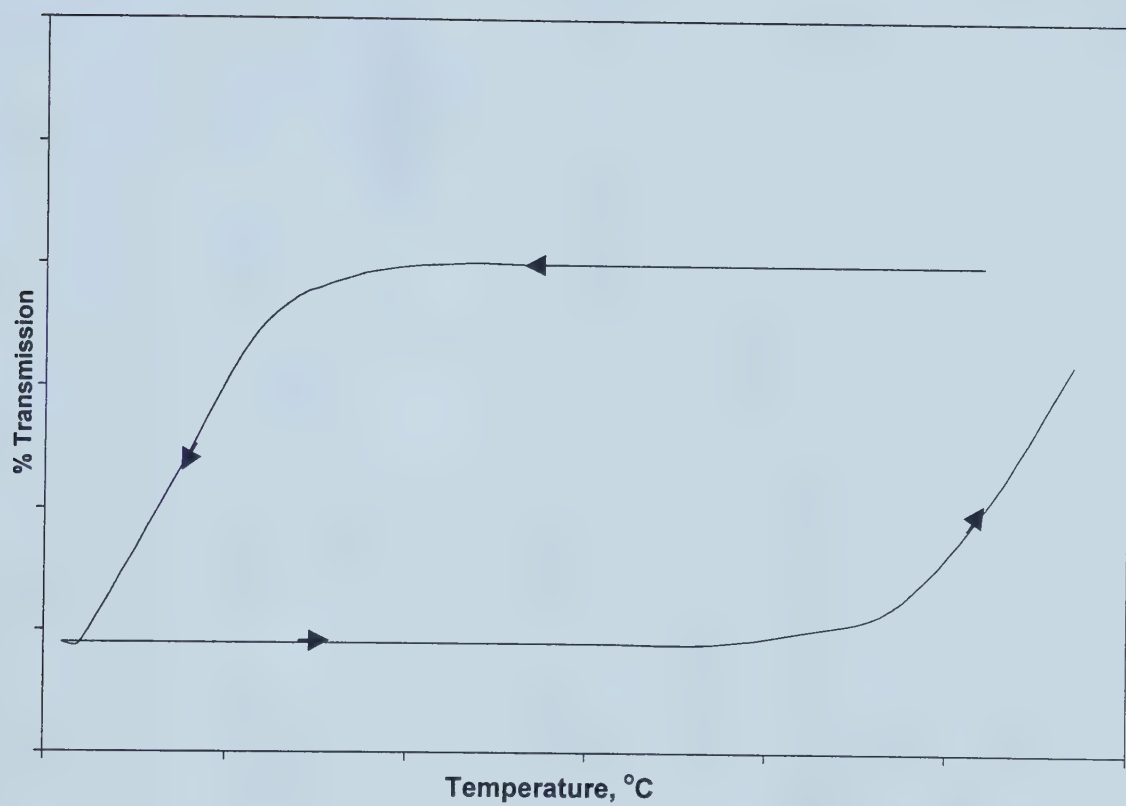
Figure 1.7. Illustration of a Cloud Point Curve (modified from Penders *et al.*, 1993.)
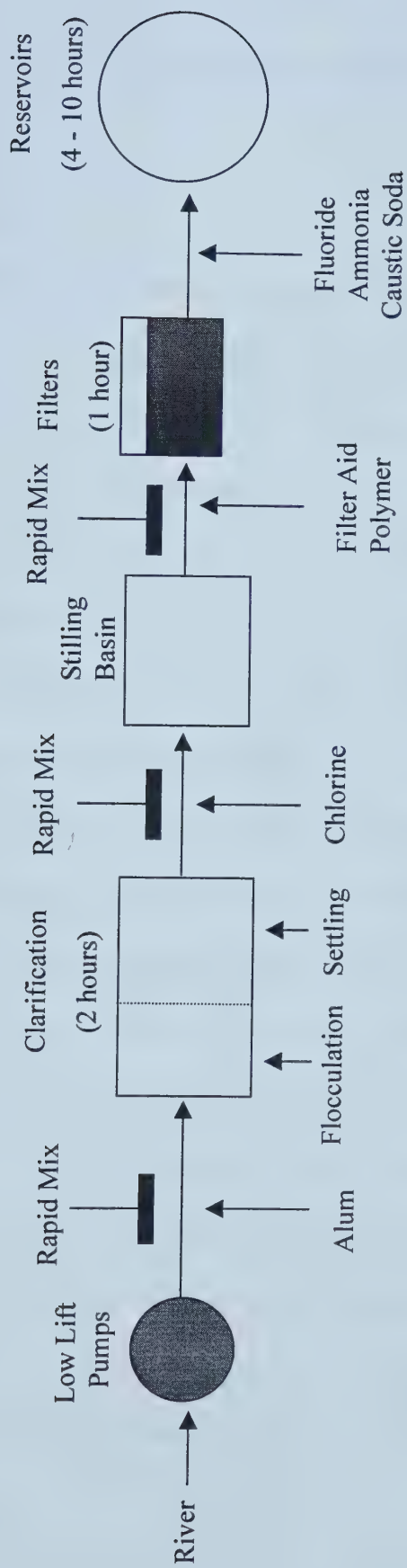
Figure 1.8. Schematic of Rossdale Water Treatment Plant.

Chapter 2

Mechanisms of Mixing

2.0 Introduction

The process of filtration is used in many water treatment plants. Filtration is usually the final stage in the water treatment process and its goal is to remove remaining suspended particles from the water. These remaining suspended particles may consist of silt and clay, colloidal and precipitated natural organic compounds, metal salts and microorganisms. The water may also contain protozoan cysts which were not inactivated by the disinfection step of the water treatment. This makes filtration an important barrier treatment (AWWA, 1990). During the operation of the filters, suspended particles are removed from the water as they accumulate within the voids between the filter media and on the top surface of the filter media. To ensure the safety and quality of the water, the filters must effectively and efficiently capture and remove particles, particularly those in the size range of protozoan cysts.

To assist in the capture and removal of particles in the filtration stage, water treatment plants use filter aid polymers. These additives change the surface properties and size of the particles in the water through destabilization and aggregation processes. It has been postulated that the filter aid polymers strengthen the attachment mechanism so that more particles adhere to the filter media and help in the conditioning of the filters during a run. The filter aid polymers are added to the filter influent stream only a few feet ahead of the filter which leaves a very short time

for the polymer to be thoroughly mixed. As a result, the polymer is usually subject to very turbulent mixing conditions prior to entering the filter.

Previous studies done by Zhu *et al.* (1996) and Li (2000), gave encouraging results about the effectiveness of filter aid polymer mixing on the water quality. These studies mainly focused on how filter aid polymers affect the destabilization and aggregation of particles in the water and how these processes in combination affect the filter performance. These studies, while focusing on the importance of destabilization and aggregation as techniques for removal of particles with filtration, focused on operating parameters rather than on the underlying mechanisms.

The main function of the filter aid polymer is to bridge particles together and for this to occur, the polymer must be dispersed into solution to contact the suspended particles. This is best achieved through turbulent mixing. Turbulent mixing disperses the polymer into the water through shear forces that are imparted mechanically. This creates intense turbulence around the impeller and it is here that polymer drops are broken apart. This drop break up increases the surface area available for diffusion of the large, but soluble polymer molecules into the water.

In addition to polymer dispersion, turbulent mixing brings particles in the water into contact with the polymer. The reactive group on the polymer adsorbs to the surface of a suspended particle and destabilizes it. This leaves other portions of the polymer molecule extending into solution which can adsorb to other particles in the water, bridging them together. Turbulent mixing is used to bring particles into contact with the particle-polymer aggregates that are formed to make the aggregates larger (AWWA, 1990). The more particles that are brought in contact with the polymer, the

larger the aggregates that will be formed. These aggregates are captured in the filters. However, some of these large aggregates may be larger than the pores in the filter leading to blockage of the entire pore. Turbulent mixing also adversely affects the aggregation of particles by creating shear forces which are strong enough to break apart the newly formed aggregates. Therefore, to optimize the use of filter aid polymers, it is necessary to understand the effect turbulent mixing has on the dispersion of the polymer and the particle capture.

The main objective of this study was to establish the effect of mixing on the dispersion of the filter aid polymers. The mixing study was conducted using a pilot plant located at the Rossdale Water Treatment Plant in Edmonton, Alberta. This pilot plant was set up to mimic the filtration stage of the full scale plant and included equipment such as mixing tanks, variable speed mixers and filters. The pilot plant included equipment for evaluating its performance such as turbidimeters, particle counters, pressure profile measurements and flow meters. To maintain as much similarity as possible between the pilot plant and the full scale plant, the influent water source for the pilot plant came from the full scale plant.

For this study, the main parameter evaluated was the filter performance which is the ultimate measure of the effectiveness of mixing. To achieve this, several measurements were taken including turbidity and particle counts of the filter effluent, the pressure profile in the filter and effluent flow rates from the filters. Turbidity and particle counts were used to evaluate the ability of the filters to capture particles. These measurements give an indication of the quality of the water. Turbidity is a measure of the relative clarity of the water and it is the standard that regulatory

agencies use when setting water quality requirements. Particle counters are a relatively new technology which can be used to determine the size and number of particles in the water. This is helpful in evaluating the water quality, as it can be used as a direct measurement of the number of particles that are of the size of *Cryptosporidium* and *Giardia*. The lower both the turbidity and particle counts, the better the quality of the water.

In addition to maintaining low turbidity and particle counts, the water treatment plant has to maximize the length of the filter runs. The longer the filter run, the more water the plant will be able to produce before the filter needs to be cleaned. To evaluate the length of the filter runs of the pilot plant, the pressure profile of the filter and the effluent flow rate from the filter were measured over the duration of the filter run. Both of these measurements are used as operating parameters by the full scale plant to indicate the end of a filter run and both give an indication of the rate at which the voids in the filter media are being blocked off.

An analysis of the effect of mixing on the dispersion of the filter aid polymer is presented in this chapter. The turbidity and particle counts of the filter effluent flow were monitored to ensure that good water quality was maintained. The main parameter used to evaluate the overall performance of the filter, with respect to mixing, was the decline of the effluent flow rate. The testing was divided into three different stages. The first stage of testing was done to analyze mixing intensity on the polymer dispersion using a low and a high rotational speed. The second stage of testing determined the impact of impeller type and size on polymer dispersion. This stage tested the performance of axial and radial impellers with diameters of 0.038,

0.076, 0.085 and 0.10 m. The final stage of testing compared the performance of a low shear axial impeller to a high shear radial impeller at similar blend times. In addition to these factors, two different types of polymers were used in the testing to determine the role of surface properties in polymer dispersion. To investigate the mechanisms involved with the dispersion of the polymer, the data collected from the pilot plant was correlated with established mixing correlations such as blend time and energy dissipation.

2.1 Experimental

2.1.1 Pilot Plant Set up

The pilot plant used for this research is located at the Epcor Water Services Rossdale Water Plant in Edmonton, Alberta. Two water sources from the full scale plant were used in this study: clarifier and stilling basin. Figure 1.8 shows the location of both basins in the water treatment process. The clarifier basin is where the first removal of particles occurs. This is where the precipitates formed by the addition and rapid mixing of the alum settle out. The clarifier removes most of the particulate from the water. The water from the clarifier was used from August of 1999 to September of 2000. Water from the stilling basin was used to test the reproducibility of the results obtained using the clarifier water. The stilling basin, which is located after the clarifier, provides contact time after chlorine addition. The water from the stilling basin was used from May to September of 2000. The turbidity, particle counts and pH of both water sources were measured continuously during testing.

The pilot plant, shown in Figure 2.1, has three square mixing tanks, each with a 7.6 liter capacity. Each mixing tank is connected to a sand filter. This allows two

simultaneous tests to be done with the same feed water while the third tank and filter are maintained as a control. All three tanks are 0.165 m x 0.165 m in cross section with a height of 0.34 m. Up-stream of each tank is a valve and a flow meter, used to regulate the flow. The exit from each tank was located 0.28 m from the bottom on the right hand side of the tank. Each tank had a variable speed mixer with a maximum rotational speed of 1500 rpm. The shafts were equipped with a coupling so that the impellers could be changed. The impellers were positioned in the tank at an off-bottom clearance of 0.025 m.

Peristaltic pumps were used to continuously inject polymer into the tank below the impeller as shown in Figure 2.2. These pumps were calibrated such that 1.8 L of polymer solution was fed continuously into the mixing tank over 24 hours to maintain a consistent concentration in the mixing tank. Due to the size of the polymer reservoir, any runs longer than 24 hours require a new batch of polymer solution.

The filter influent stream comes directly from the mixing tanks. The filters are Plexiglas columns with an inside diameter of 0.15 m filled to a height of 0.70 to 0.75 m with 0.35 mm sand. The filters are open to the atmosphere at the top and are operated at constant head in declining rate mode. The headloss profile along the filter media column was measured using five piezometers located at 0.15 m intervals on the right hand side of the column. Each filter was also equipped with a flow meter and valve on the effluent piping. The flow meters were used to measure the effluent flow rate from the filter. The headloss measurements and the filter effluent flow rates were recorded every few hours. When a negative headloss in the filters was observed, the

run was ended. A negative headloss measurement means that no water is flowing through that filter.

The effluent from each filter was passed through a turbidimeter and particle counter. The turbidity and particle counts were measured using 1720D on-line turbidity meters and Met One model PCX particle count sensors, respectively. The data for the on-line turbidity meters and particle counters were continuously recorded by a computer. Due to ongoing problems with the on-line particle counters, a portable particle counter was used for some of the testing. The portable particle counter gave grab sample data and was not recorded by the computer.

After the completion of each run, the filters were backwashed. The filters were first subjected to three minutes of air scouring and then to a ten minute water wash. The wash water used to clean the filters came from the service line in the plant which contains treated water. Operating procedures for the pilot plant are given in Appendix I.

This study focuses on filter aid polymers with respect to particle capture and requires consistent preparation of the polymer feed solution for the pilot plant. The polymer solution must be prepared such that the right concentration is obtained in the tank and the stock solution is well mixed. The following section outlines the procedure used to prepare the polymer solutions for the pilot plant.

2.1.2 Polymer Preparation

Two commercial polymers were used in this study. One polymer is made by Calgon Corporation and the other polymer by Allied Colloids Inc. The polymer supplied by Calgon is Pol-E-Z-652 which is a polyacrylamide, non-ionic polymer

with a high molecular weight supplied in emulsion form (Calgon Product Information sheet, 1999). The polymer supplied by Allied Colloids is Percol LT7996 which is a cationic, low molecular weight polymer with a high charge density. The LT7996 is supplied as a low viscosity solution which is soluble in water (Allied Colloids Product Information sheet, 1999).

The vendor supplied polymer solutions were used to prepare a high concentration stock solution (1g/L) which was then diluted down to the specific working concentration. The stock and working solutions were prepared in one and two liter flasks, respectively. The stock solutions were discarded after five days as the polymer begins to disintegrate after that time. The working solutions were made fresh daily. It is important that the procedures for preparing both the stock solutions and working solutions not be modified as any modifications can have an effect on the initial mixing and dispersion kinetics of the polymer.

The 1 g/l polymer stock solution is prepared by measuring out one gram of the vendor polymer solution. The polymer is then transferred to a one liter glass volumetric flask containing a small amount of water. The polymer readily adheres to glass surfaces so it is important to have water in the flask when the polymer is added. To remove any of the polymer that attaches to the sides of the flask, the flask is rinsed with water. After all of the polymer is transferred, the flask is filled to about one quarter full and inverted several times to mix the polymer. The flask is then filled to the one liter mark and inverted repeatedly for five minutes.

The amount of stock solution required for the necessary concentration of the working solution was calculated using the formula given in Appendix II. A graduated

glass cylinder was used to measure out the desired amount of stock solution. The solution was then transferred into a two liter glass volumetric flask and the graduated cylinder was rinsed with water. The volumetric flask was then filled to the two liter level with water and inverted repeatedly for five minutes. The mixed polymer solution was then transferred to a two liter plastic graduated cylinder which is used as the polymer reservoir for the peristaltic pumps.

2.1.3 Measures of Filter Performance

To evaluate the performance of a filter, there are two types of measurements that can be used. One type evaluates the filter performance with respect to particle capture, the other with respect to operating parameters. The first category of measurements includes turbidity and particle counts of the filter effluent. While turbidity gives a gross measure of the amount of particles remaining in the water, particle counters give the number of particles in the water within a specific size range. In addition to evaluating the quality of the filter effluent, it is important to monitor the operation of the filters in terms of operating parameters such as the pressure profile of the filter (headloss) and effluent flow rates. These parameters give an indication of how fast the filter voids are being blocked off and how much longer the filter will run before needing to be backwashed. Combining the data from the water quality analysis and from the filter operation gives a well defined picture of the overall filter performance. More detailed descriptions of the turbidity, particle counters, pressure profile and effluent flow rate measurements follow.

2.1.3.1 Turbidimeter

The on-line turbidimeter is a 1720D Sensor from the Hach Company as shown in Figure 2.3. The turbidimeter consists of a 1720D head assembly, 1720D body and a PS 1201 power supply. This turbidimeter is a continuous reading nephelometric turbidimeter designed for low range turbidity monitoring. Nephelometric refers to the way the instrument estimates how the light is scattered.

A sample stream from the filter effluent was continuously fed into the turbidimeter and flows through the baffle network of a bubble trap before entering the body of the turbidimeter. This is done to avoid getting false readings due to bubbles. The turbidity of the sample is measured by directing a strong beam of light from the sensor head assembly down into the sample in the turbidimeter body. The light that is scattered at 90° by suspended particles in the sample is detected by a submerged photocell. The amount of light that is scattered is proportional to the turbidity of the sample. A high turbidity sample will cause a high level of light scattering while low turbidity samples cause a small amount of light to be scattered (Hach Company Manual, 1998). The sample exits the turbidimeter by spilling over the weir into the drain port.

The AquaTrend Module is the control module and data acquisition system for the 1720D sensor. Each turbidimeter is assigned a separate channel on the AquaTrend Module to which the information was recorded. A reading was taken every three seconds and the output from each turbidimeter was recorded by the computer (Hach Company Manual, 1998).

Turbidimeters are the standard equipment currently used for evaluation of effluent water quality in a water treatment plant. Although regulator agencies specify effluent requirements in turbidities, this measurement technique does not give any indication of the size distribution of the light scattering particles. According to Hargesheimer and Lewis (1995), for filtered water with turbidity measurements less than 0.1 NTU, a broad range of particle count values is possible. Turbidity can not distinguish between the size of particles in the water as it monitors the clarity of the water. Particle counters are starting to be used in an effort to increase water safety by monitoring the effluent water for particles in size range of *Cryptosporidium* and *Giardia*.

2.1.3.2 On-Line Particle Counters

The on-line particle counters installed at the pilot plant are Met One PCX particle counters shown in Figure 2.4. The Met One contains laser-diode-based particle counting sensors. The water sample is fed continuously into the sensor at a flow rate of 100 milliliters per minute and is funneled through an optical flow cell. As particles pass through the sensor they generate a signal corresponding to their size (Met One Product Manual, 1997). The sensors, which are equipped with a calibration curve illustrating the signal response with respect to the size of the particle, counts the number of particles in a size range and stores it in memory. The data from the particle counters is collected by the Met One "Vista" data collection software program which displays the normalized count (counts/ml) based on the selected size range, count period and flow rate (Met One Product Manual, 1997). The data is recorded using the WaterWare Data Acquisition system which displays particle

counts for the following sizes: greater than two microns, two to three microns, three to five microns, five to seven microns, seven to ten microns, ten to 15 microns and greater than 15 microns. The computer records the data every five minutes.

Particle counters can provide a more sensitive measurement of particulate content than turbidimeters for particles larger than one micron (Van Gelder *et al.*, 1999). Unfortunately, the data obtained from the on-line particle counters in the pilot plant could not be used due to continuous calibration problems.

2.1.3.3 Portable Particle Counter

Due to ongoing problems with the on-line particle counters, a portable particle counter, Model WGS-267 Water Grab Sampler, was used and is shown in Figure 2.5. The main panel of the sampler contains the sampling tube ports, DC pump switch, batteries, flow control, flow meter and particle counter sensor.

For the testing at the pilot plant, the particle counter was set to count the number of particles with a size greater than two microns and the sampling time of the particle counter was five seconds. The concentration (CONCEN) mode was used for the testing. This mode gives a quick calculation of the particle concentration by averaging the number of particles counted in one second periods and gives the calculation in counts-per-milliliter of water.

For the CONCEN mode, grab sampling was used. To take a grab sample, the tubing from the on-line particle counter was inserted in to the SAMPLE IN connection. The pump was started and set to operate at a flow rate of 100 milliliters per minute. The liquid sample was then pumped through the sensor which uses a laser diode source and collection optics to detect particles. Particles in the water interrupt

the light energy from the laser diode creating a shadow. A photo diode converts these shadows into electrical pulses. The height of the electrical pulse created is proportional to the particle size. The pulses are counted and their intensities are measured to determine the particle size (Met One Model WSG-267 Water Grab Sampler Manual, 1995). The particle count readings were recorded manually and were taken every couple of hours throughout the filter run. Even though the grab sampler was used, the results could not be used for comparison as there is not a complete data set due to lag time in obtaining the sampler.

2.1.3.4 Headloss Measurements

Headloss measurements were taken from the piezometers which are located on the side of the filters as shown in Figure 2.6. One end of the piezometer is located in the center of the media while the other is attached to plastic tubing which runs up the side of the filter to the top of it. Mounted behind each piezometer tube is a measuring stick used to measure the height of liquid in the tube. The headloss measurement was taken every couple of hours throughout the filter run, including at the beginning and end of the run.

2.1.3.5 Effluent Flow Rates

Rotameters are located on the effluent stream from the filters and were used to monitor the flow rate through the filter in liters per minute. The effluent flow rate measurements were taken every couple of hours until no flow could be detected.

2.2 Experimental Design

The experimental work was divided into three sections corresponding to the three objectives of the study: effect of mixing, effect of impeller type and comparison of a

low shear axial impeller and a high shear radial impeller. The first section examined the effect of mixing intensity on the dispersion of the polymer. Based on the results of a previous study by Li (2000) on optimizing polymer dosage, the Pol-E-Z-652 polymer at a concentration of 0.04 mg/ml was selected for this set of experiments. The mixer, equipped with a 0.05 m diameter paddle impeller, was operated at rotational speeds of 250 and 1400 rpm (G = 125 s^{-1} and 1245 s^{-1}). These mixing conditions give blend times of 15.5 and 3.5 seconds, respectively. The water used in this testing came from the clarifier basin. For all runs, the water enters the mixing tank through the bottom of the tank below the impeller at a rate of 3 L/min. At this flow rate, the mean residence time in the tank is 152 seconds. For the control runs, the Pol-E-Z- 652 polymer was fed at a concentration of 0.04 mg/ml and agitated using a 0.05 m diameter paddle impeller rotating at 250 rpm.

The second section tests the effect of impeller size and impeller type on the dispersion of the polymer. Table 2.1 lists the impeller types, sizes and rotational speeds used in the testing along with the various measures of mixing for each run which are referenced to the control conditions. The water source for this testing was the clarifier basin.

The final set of experiments was done to compare the effect of different impellers on the polymer dispersion. For this testing, a 0.076 m diameter Rushton Turbine and the 0.085 m diameter A310 impeller were run at the same blend time. The corresponding conditions for these experiments are given in Table 2.2. The Percol LT7996 polymer at a concentration of 0.25 mg/ml was used in this set of experiments to determine if surface properties affect the polymer dispersion as the

LT7996 has different characteristics than the Pol-E-Z-652. The water source for this set of experiments was the clarifier basin.

2.3 Results and Discussion

Of the measures of filter performance discussed in section 2.1.3, the filter run time proved to be the most reliable. The turbidity readings from the filter effluent for all of the experiments stabilized in the range of 0.04 to 0.09 NTU, regardless of the fluctuations in the influent turbidity. This range is well below the government regulations and indicates a good quality effluent. However, since this range is very narrow, it is difficult to determine if the difference in the turbidity reading is due to the mixing conditions or due to noise and drift in the readings. The headloss profiles of the filters were predominantly the same through out the experiments. The results of these profiles will be discussed in more depth later in the chapter. The effluent flow rate measurements were used to evaluate the filter performance. The rate of decline of the effluent flow rate was used as an indication of the filter run length. Filter run length is the length of time a filter operates before headloss reaches a maximum.

2.3.1 Effect of Mixing on Filter Performance

Figure 2.7 shows the effect of mixing intensity on the effluent flow rate as a function of time for the experiments performed using the 0.05 m diameter paddle impeller. At a polymer dose of 0.04 mg/ml, the filter obtained a run length of 24 hours at the high mixing intensity of 1400 rpm ($G = 1245$ s^{-1}). The lower mixing intensity of 250 rpm ($G = 125$ s^{-1}) resulted in a much shorter filter run time of 11 hours.

This trend is consistent with those found by Zhu *et al.* (1996) and Li (2000). The study by Zhu *et al.* (1996) examined the effect of mixing on only one polymer and used the time at which turbidity breakthrough occurs to determine the filter run length. The results from this study are shown in Figure 2.8. According to Zhu *et al.* (1996), mixing intensities within a range from 700 to 1100 s^{-1} resulted in filter run times longer than three days; however, when the intensity was reduced to 400 and 100 s^{-1} the time required for turbidity breakthrough to occur was much less.

The study done by Li (2000) tested the effect of mixing on three types of polymers, including the Pol-E-Z-652 polymer. The results from this study are shown in Figures 2.9 to 2.11. Li (2000) found that as the mixing rate was increased the filter effluent particle counts and turbidities were lower and the filter run times were longer. However, Figure 2.10 shows that even though the particle count for the lower mixing intensity increases, the turbidity measurement does not fluctuate indicating that the particle count data is more informative than the turbidity data. The data from this study also shows that the effect of mixing persists for different types of polymers. This study tested, in addition to the Pol-E-Z-652 polymer, the Percol LT-24 which is a medium molecular weight, cationic polyacrylamide polymer and Nalcolyte 8100 which is a cationic polyamine polymer.

With a consistent trend in three separate studies, this study was undertaken to investigate the mechanisms involved in polymer mixing and filter performance. It was initially assumed that the completely soluble filter aid polymer used in the experiments is also completely miscible and thus requires only short mixing times to reach the equilibrium condition of complete dispersion. Since the batch blend times in

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the tank are relatively short (3.5 and 15.5 s) compared to the residence time in the tank (152 s), the tank is assumed to be completely back-mixed and the polymer should be well dispersed. In addition to the dispersion of the polymer, mixing drives the polymer-particle collisions that are required for the destabilization and aggregation of particles. Mixing transports the polymer to the surface of a particle where the polymer adsorbs. Once the polymer has adsorbed to the particle, mixing brings the polymer in contact with other particles in the water which may attach to other sites on the polymer (Akers, 1987). This leads to particles being bridged together by the polymer and forming aggregates that are stronger and more resistant to shear forces (AWWA, 1990). As the diameter of an aggregate increases, the shear stress on the aggregate also increases. Once the aggregate exceeds the maximum stable diameter for a given velocity gradient, the aggregate will undergo break up through the mechanism of aggregate splitting or surface erosion of primary particles. A higher shear rate will increase the speed of these mechanisms (Ghosh *et al.*, 1985). A lower mixing intensity does not create as much shear force and this results in the formation of larger aggregates. Reynolds and Richards (1991) hypothesized that larger aggregates clog the top pore spaces of the filter resulting in short filter run times. A higher mixing intensity can continually break up aggregates larger than the maximum stable diameter. These smaller aggregates penetrate deeper into the filter before being captured. Once these smaller aggregates are attached to the filter, they capture other suspended particles and aggregates that come in contact with them as they travel through the filter. Any un-reacted polymer residuals also provide a bridging mechanism between the filter media and previously deposited aggregates

(Zhu *et al.*, 1996). This accumulation of aggregates causes the pore spaces to become narrower and the velocity through the pore to increase, driving aggregates deeper into the filters. The smaller aggregate size leads to longer run time than large aggregates as the penetration of particles into the filter bed is deeper (Reynolds and Richards, 1991).

In addition to removing suspended particles, the filter aid polymers accelerate the initial ripening of the filter. Ripening is the initial improvement in removal efficiency after backwashing that occurs as retained particles begin to serve as collectors.

Although a consistent effect of mixing is seen in Figures 2.7 through 2.11, the paddle impellers used in the first part of this study are not the best equipment for achieving good mixing. Paddle impellers have a small pumping capacity (a slow axial flow) that does not provide a thorough mixing of the tank volume. According to Cheremisinoff (1995), perfect mixing is attained only in a thin stratum of liquid directly around the impeller. The paddle impeller produces slow circulation in that tank resulting in less turbulence convected throughout the tank. This is indicated by a lower power number. Better mixing could be obtained if the blades were inclined as this increases the axial flow. Other impeller designs, such as the Rushton turbine, pitched blade turbine and the A310 impeller have well defined flow patterns and mixing characteristics and have been shown to be effective in different types of mixing applications.

2.3.2 Determination of Mixing Mechanism through varying impeller type, diameter and rotational speed

Comparing the performance of various impellers will determine whether the mechanism of particle capture is dominated by turbulence or bulk flow. Table 2.1 shows the various impeller types, diameters and rotational speeds that were used which are referenced to the control conditions. Included in this table are calculations for the blend time, energy dissipation, mean shear and Reynolds number. All of the impellers were operated in the turbulent regime except for the 0.038 m diameter impellers at a rotational speed of 250 rpm. The main measure for evaluating the impeller performance was the filter cap off time, which represents the total time for the filter run. According to Masschelein (1992), the total headloss of a filter bed is in inverse ratio to the depth of penetration of the suspended particles. A high headloss measurement resulting after a short time period indicates that most of the aggregates are being captured at the top of the filter. A low headloss measurement after a long time period indicates that the aggregates are penetrating deep into the filter. To determine if particle capture is occurring predominately at top of the filter, the total headloss across the filter was compared to the cap off time for the various impellers as shown in Figure 2.12. The data is scattered and no conclusion can be drawn. According to Stevenson (1997), most of the headloss in the filter occurs within the fully clogged part of the bed therefore, the total headloss across the filter does not give an indication of why the filter is clogging off. The use of a headloss gradient analysis as illustrated in Figure 2.13 is more useful to determine this. This figure is plotted with the media height versus headloss and according to Zhu et al. (1996), the

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negative inverse of the curved slope represents the headloss gradient. The greater the headloss gradient, the greater the headloss per unit length of the filter media. If large aggregates are formed, they will be captured in the top part of the filter. In this case most of the headloss will occur near the top of the filter. If the headloss is distributed evenly along the bed, particles were able to penetrate deep into the bed (Zhu *et al.*, 1996). As illustrated in Figure 2.13, the top of the filter is being clogged and a cap is being formed. Underneath the capped area of the filter, there is a linear pressure profile along the remainder of the filter bed. With the exception of a few runs, all of the headloss occurred in the top of the filter suggesting that particle removal is due to interstitial straining mechanisms rather than depth penetration.

Turbulent mixing is used to transfer energy from the impeller into the liquid in the tank. This transfer of energy helps to disperse the polymer and to reduce the size of the initial polymer drops. The energy imparted into the tank reduces the polymer drops down to a size where molecular diffusion dominates. If the polymer drops are not reduced in size, the time it takes to achieve homogeneous conditions is considerable as molecular diffusion is a slow process due to the molecular weight of the polymer. Therefore, to minimize the time required for molecular diffusion to occur, the drop sizes must be reduced to the smallest length scale. To determine if the mixing is dominated by a large or a small scale, the filter cap off time for the different runs were correlated to established mixing correlations. Correlations such as energy dissipation at the impeller, energy dissipation in the bulk and mean circulation time in the tank are used to describe the flow within a stirred tank. The energy dissipation at the impeller (ε_I) is used to characterize the level of turbulence at the impeller and

represents the smallest time scale. This parameter is defined as the power per unit mass in the impeller swept volume $(P/\rho V_I)$ and is proportional to $N_p N^3 D^2$. The energy dissipation in the bulk (ε_B) is defined as the power per unit mass in the tank $(P/\rho V_{tank})$ and is proportional to $N_p N^3 D^2 (D/T)^3$ (Zhou and Kresta, 1998). The circulation time in the tank (θ_{tank}) is proportional to $N^{-1}(T/D)^3$. Instead of evaluating the energy dissipation in the bulk and the circulation time in the tank separately, the blend time can be used as it incorporates both of these correlations. The blend time (θ_B) is a representation of the macroscale mixing and represents the largest time scale. The blend time is inversely proportional to ND^2.

Since no conclusions could be drawn from the previous analyses, the filter cap off data was compared separately to ε_I and θ_B. Figure 2.14 shows the data for ε_I in relation to the filter cap off times. This comparison was done to determine if the local turbulence at the impeller is a dominant factor. The level of turbulence at the impeller has a direct effect on the break up of the polymer drops. Figure 2.14 shows that the data are scattered indicating that local turbulence at the impeller is not the dominating factor. There is no indication that a higher energy dissipation rate (higher amount of turbulence) results in better filter performance than a low energy dissipation rate. The calculated energy dissipation rates for the different impellers are given in Table 2.1 with respect to control conditions.

When the filter cap off time was related to the corresponding blend times, the data was also scattered. This indicated that blend time is not the dominating factor. There is no indication that a shorter blend time results in better filter performance

than a longer blend time. The calculated blend times for each impeller are given in Table 2.1 with respect to control conditions.

According to Zhou and Kresta (1998), the interaction between mean circulation time and level of the turbulence at the impeller determines the drop break up and coalescence rates of the polymer. Relating the filter cap off data from the pilot plant to a combination of energy dissipation at the impeller and blend time will give an indication of how the combination of circulation time and turbulence at the impeller affect the dispersion of the polymer in the tank. The comparison of filter cap off time to the ratio of ε_I to θ_B shows that the data are scattered as illustrated in Figure 2.15. Therefore, no conclusions could be made about how these factors in combination affect the polymer drop break up.

To determine if the tank is completely back mixed, the filter cap off time was compared to the ratio of mean tank residence time in the tank to blend time as shown in Figure 2.16. This figure shows that consistent filter performance is obtained when the mean tank residence time is greater than 75 blend times. This indicates that lower blend times or longer residence times are required to achieve consistent results.

The scattered data indicates that the assumption of the polymer being completely miscible may be incorrect and that the surface properties of the polymer may be interacting with the mixing. If the polymer is not completely miscible, a liquid-liquid system may exist which requires considerably longer mixing times to reach equilibrium than are available in the pilot plant. If the polymer is not completely miscible, the residence time in the tank is not long enough for the mixing to reduce the size of the initial polymer drops before they enter the filter. This results

in the headloss occurring at the top of the filter. Unfortunately, the type of data collected from the pilot plant can not be used to define the dispersion kinetics of the polymer or their connection with turbulent mixing.

The difficulty encountered in deciphering these results indicated that the initial experimental design was too broad. In addition to being too broad, the experimental design created undesirable conditions. When the small impellers were operated at the lowest rotational speed not enough turbulence was created in the tank to keep particles suspended in the water. At the highest rotational speed, the 0.076 m diameter Rushton turbine and the 0.10 m diameter A310 impeller would create high amounts of turbulence, causing water to flow over the sides of the mixing tanks.

2.3.3. Effect of Bulk Flow and Turbulence on Filter Performance

To eliminate these undesirable conditions, the experimental design for the final set of experiments was altered to evaluate the performance of one low shear axial impeller and one high shear radial impeller with respect to particle capture. For these tests, the Rushton turbine and the A310 impeller were operated with equal blend times. In addition to testing only two impellers, the Percol LT7996 polymer was used for this set of experiments. The different polymer was used in this experiment to verify the hypothesis that surface properties of the polymer affect its dispersion. The Percol LT7996 is a cationic polymer and the predominant destabilization mechanism is charge neutralization with polymer bridging playing only an minor role (Gregory and De Moor, 1984). The LT7996 polymer is a low molecular weight polymer and once it attaches to a particle there is little extension of the polymer into the liquid phase reducing the chance of particle bridging.

At the applied polymer dose of 0.25 mg/ml, there is little effect of mixing seen with the change in polymer type and concentration as shown in Figure 2.17. The higher blend time (lower rpm) resulted in longer filter run times but the overall performance of the filter with respect to the decline in effluent flow rate for the two impellers are similar, regardless of the blend time. Since the mixing intensities varied between the impellers for the two different blend times, the results should have shown an effect of mixing between the different blend times. The fact that this is not seen indicates that other factors, such as surface properties, may have an effect on the dispersion of a soluble polymer.

The results from this final section indicate that the mechanism of particle capture is not the dominant issue. The polymer dispersion in the tank is more important as it directly affects the penetration of polymer into the filter, thus affecting the operability of the filters.

2.4 Conclusions

Based on the experimental results, the following conclusions were drawn.

1. The filter performance was significantly affected by mixing intensity during the addition of the filter aid polymer to the water as shown in Figures 2.7 through 2.11. High mixing intensity resulted in filter run times of 24 hours compared to only 11 hours for runs conducted at the low mixing intensity. Comparing the ratio of mean residence time in the tank to the blend time for both mixing intensities shows that for the low mixing intensity the ratio is 10 where as for the high mixing intensity the ratio is 45, which is 4.5 times longer.

2. The headloss profile across the media for various impeller types and sizes suggests that most of the headloss is occurring at the top of the filter as illustrated in Figure 2.13. This indicates that there exist polymer aggregates that are large enough to block the top pores of the filter. This suggests that the polymer is not completely miscible at test conditions and requires a longer mixing time to achieve homogeneous conditions.

3. The pilot plant data did not correlate with any established measures of mixing as shown in Figures 2.14 and 2.15. A consistent trend was found when the mean residence time is greater than 75 blend times as shown in Figure 2.16. In other cases, mixing had no effect (Figure 2.17). This suggests another important mechanism, not addressed in the current experimental design. This mechanism is investigated further in the next chapter.

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Table 2.1.Experimental Conditions with respect to control conditions

Impeller	D/D_{ref}	N/N_{ref}	Np	G/G_{ref}	$\varepsilon_I/\varepsilon_{I, ref}$	Re/Re_{ref}	θ_B/θ_{Bref}	Cap off Time (hr)
Ref. Paddle	5.08 cm	250 rpm	4.92	125 s^{-1}	0.90 m^2/s^3	1.08×10^4	15.5 s	
Rushton	0.75	1	4.75	0.5	0.5	0.6	1.8	4
	0.75	3.2	5.5	3.0	20.6	1.8	0.5	6.5
	0.75	6	5.5	7.6	135.0	3.4	0.3	3.5
	1.5	1	5.5	2.9	2.5	2.3	0.4	4.5
	1.5	3.2	5.5	16.8	82.4	7.2	0.1	4
	1.5	4.8	5.5	30.0	278.0	10.8	0.09	7
PBT	0.75	1	1.76	0.3	0.20	0.6	2.5	4.5
	0.75	3.2	1.3	1.4	4.9	1.8	0.9	7
	0.75	6	1.3	3.7	32.1	3.4	0.5	7.75
	1.5	1	1.3	1.4	0.6	2.3	0.7	4
	1.5	3.2	1.3	8.2	19.4	7.2	0.2	6.5
	1.5	6	1.3	20.9	128.4	13.5	0.1	7
Paddle	0.75	1	4.87	0.5	0.56	0.6	1.8	7.25
	0.75	3.2	2.75	2.1	10.3	1.8	0.7	4.5
	0.75	6	2.75	5.4	67.9	3.4	0.3	9
	1	1	4.92	1	1	1	1	15
	1	5.6	2.75	10.0	98.1	5.6	0.2	24
	1.5	1	2.75	2.1	1.3	2.3	0.5	6.5
	1.5	3.2	2.75	11.8	41.2	7.2	0.17	6
	1.5	6	2.75	30.4	271.6	13.5	0.09	7
A310	1.7	1	0.3	0.9	0.17	2.9	0.9	3.5
	1.7	3.2	0.3	5.2	5.5	9.0	0.3	3
	1.7	6	0.3	13.2	36.9	16.8	0.15	7
	2.0	1	0.3	1.4	0.23	4.0	0.6	4.25
	2.0	3.2	0.3	7.7	7.7	12.4	0.2	4.25
	2.0	6	0.3	19.8	51.0	23.3	0.1	7.25

Table 2.2. Experimental Design for Blend Time Experiments.

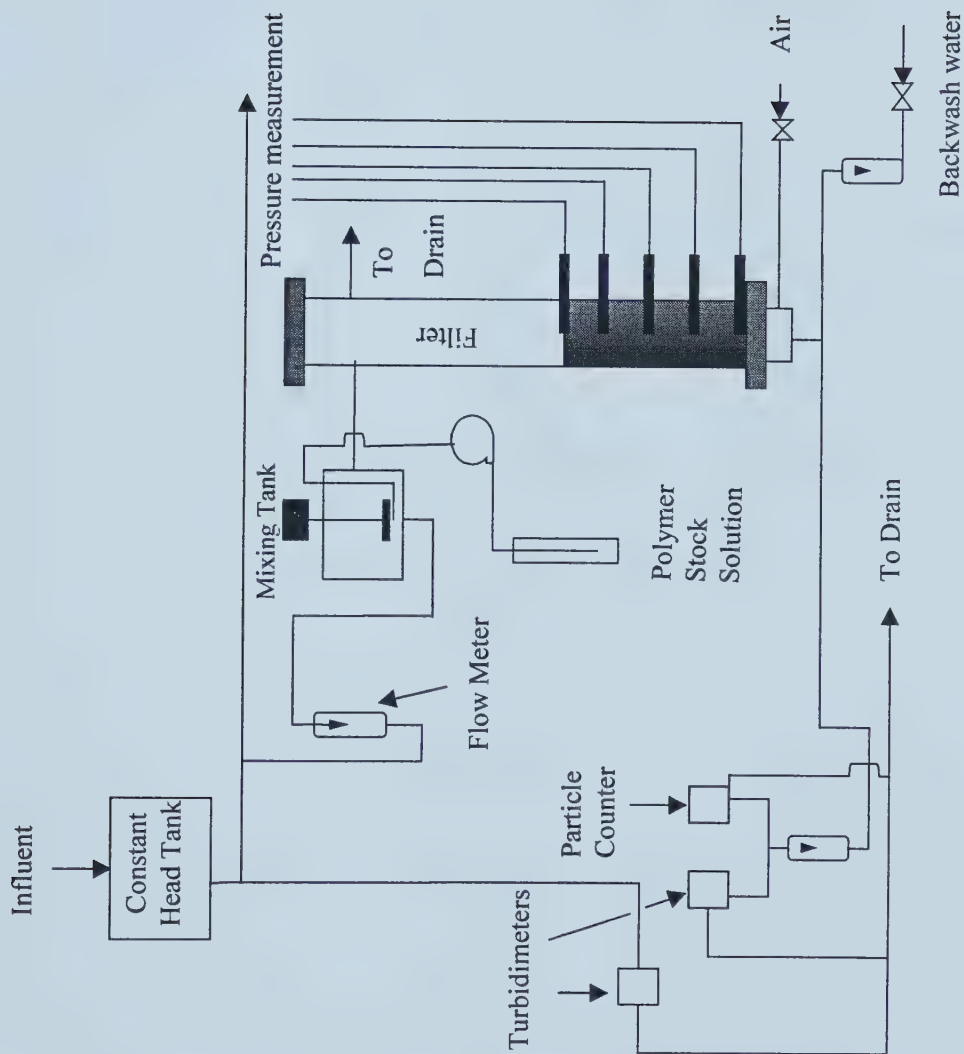| Blend Time (s)	Impeller	Rotational Speed (rpm)	G (s^{-1})
3.0	Rushton Turbine	560	1225
	A310	1400	1490
4.5	Rushton Turbine	360	630
	A310	800	645

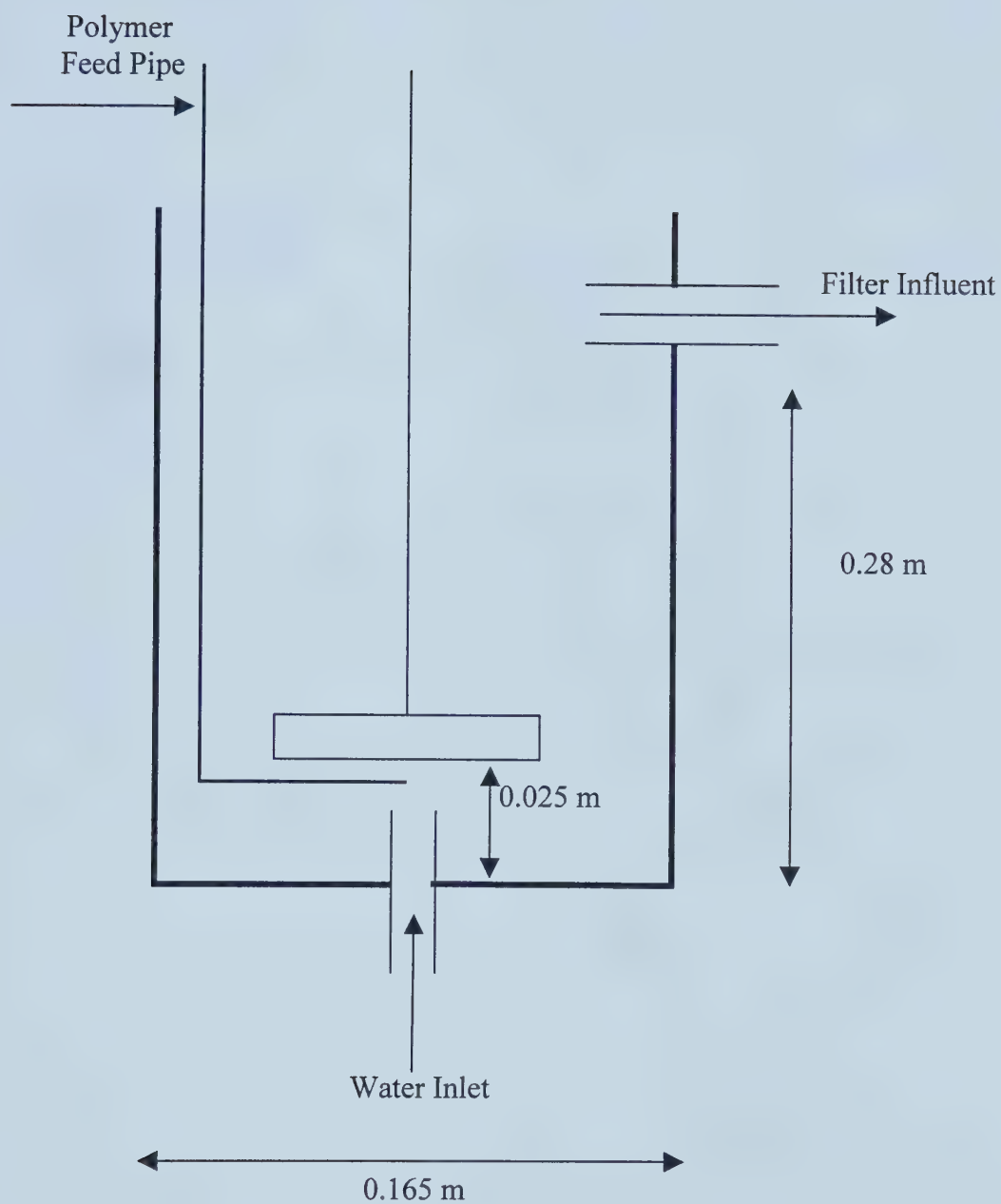**Figure 2.1. Schematic of One of Three Mixing and Filtration Trains in the Pilot Plant**

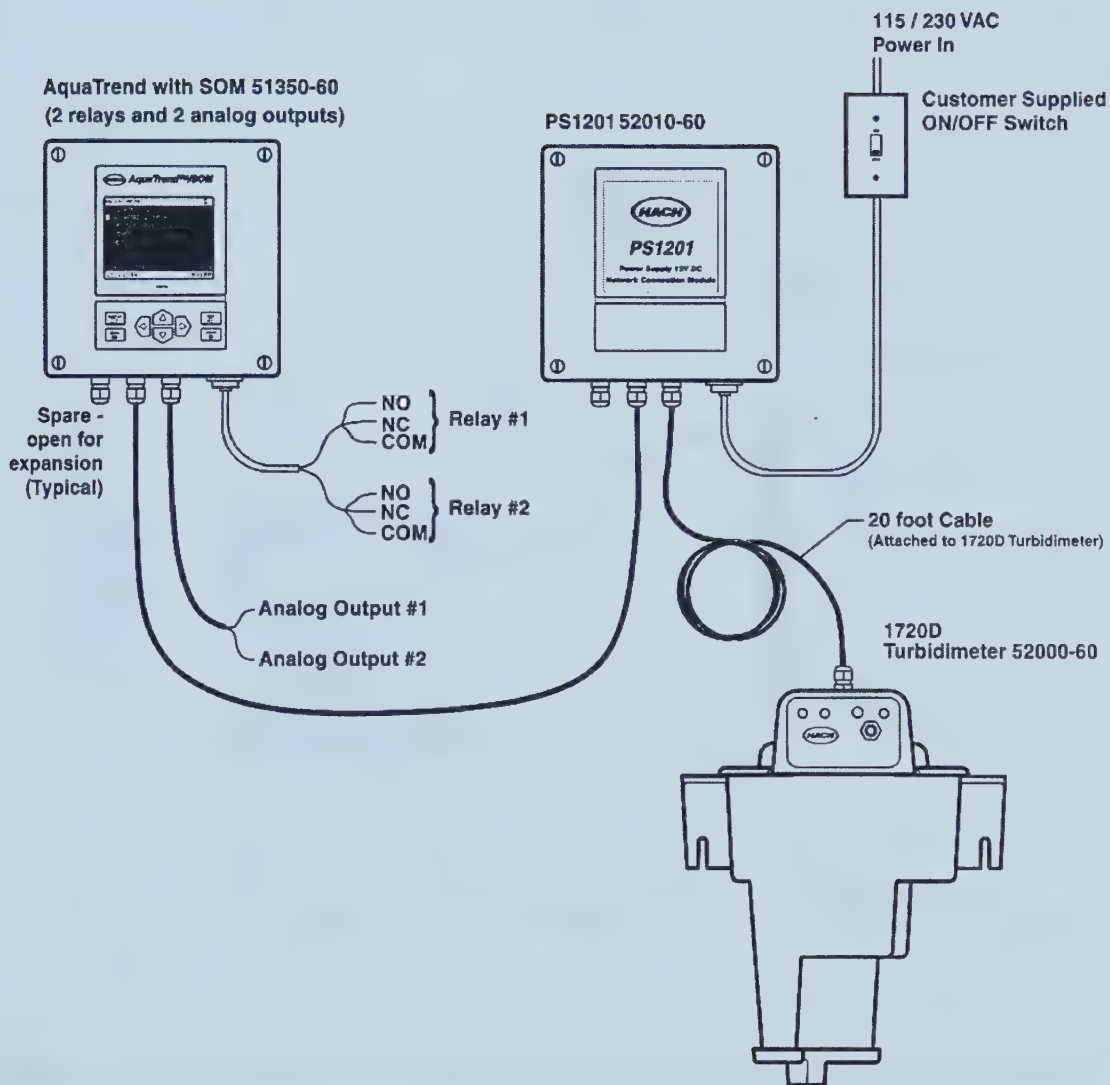**Figure 2.2. Dimensions of Square Mixing Tanks in Pilot Plant**

AquaTrend with SOM 51350-60
(2 relays and 2 analog outputs)

PS1201 52010-60

115 / 230 VAC
Power In

Customer Supplied
ON/OFF Switch

PS1201
Power Supply 12V DC
Network Connection Module

Spare -
open for
expansion
(Typical)

NO
NC
COM } Relay #1

NO
NC
COM } Relay #2

20 foot Cable
(Attached to 1720D Turbidimeter)

Analog Output #1

Analog Output #2

1720D
Turbidimeter 52000-60

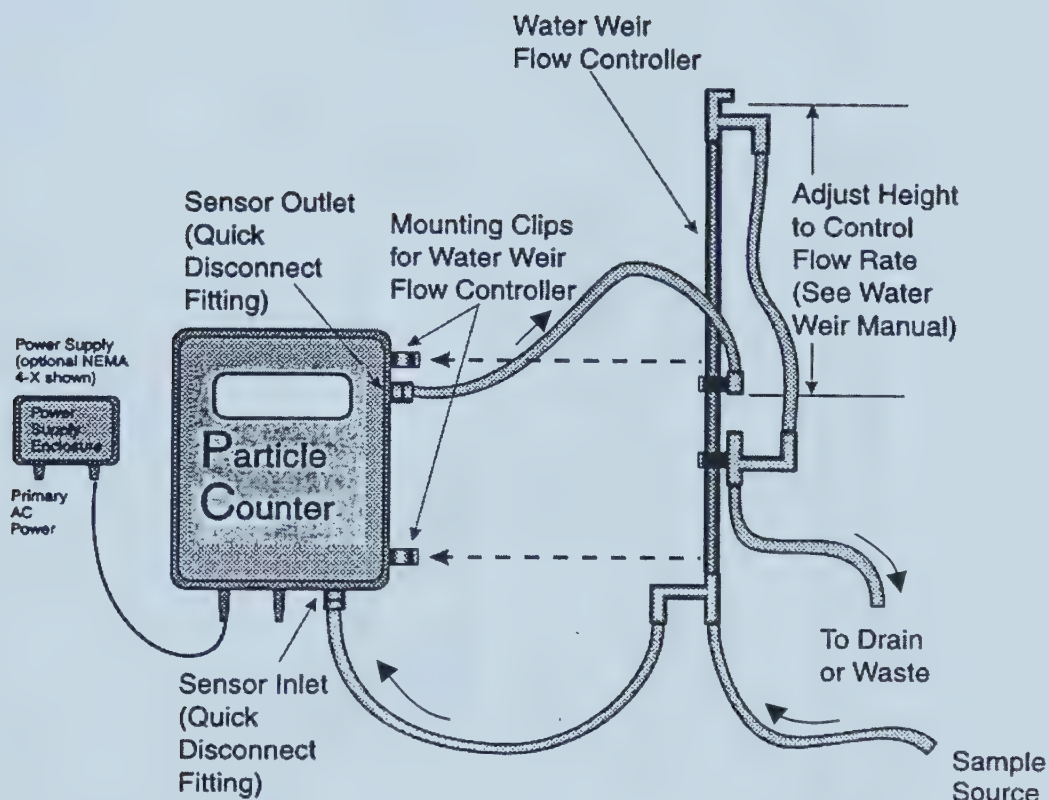Figure 2.3. Basic 1720D Turbidimeter System (Hach Company Manual, 1998)

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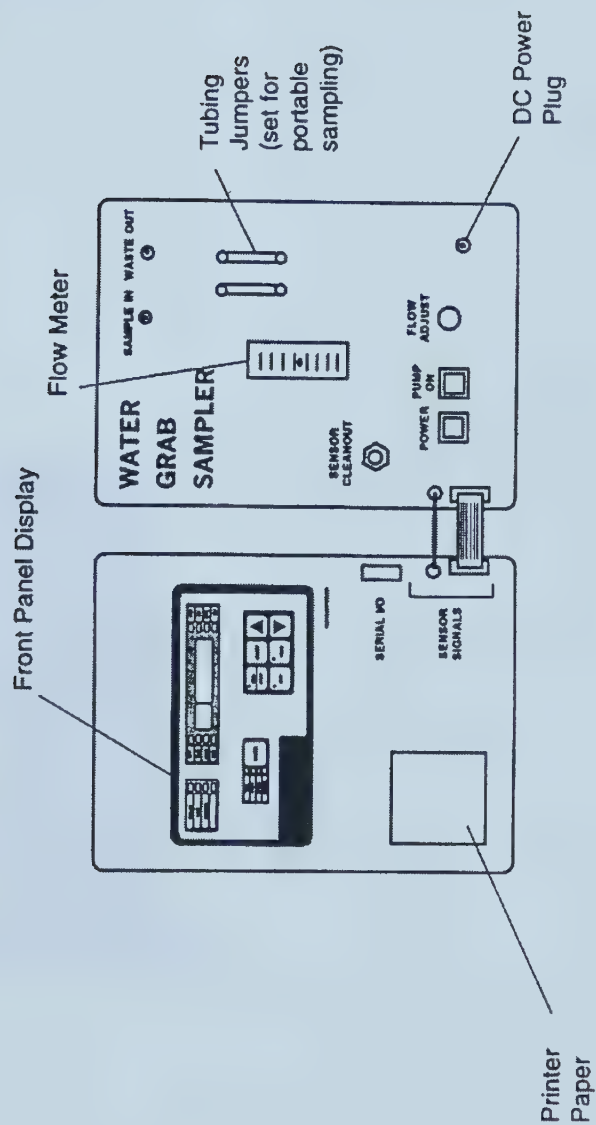**Figure 2.4. Met One PCX Particle Counter (Met One Product Manual, 1997)**

Figure 2.5. WSG-267 Water Grab Sampler Primary Components (Met One Model WGS-267 Water Grab Sampler Manual, 1995).
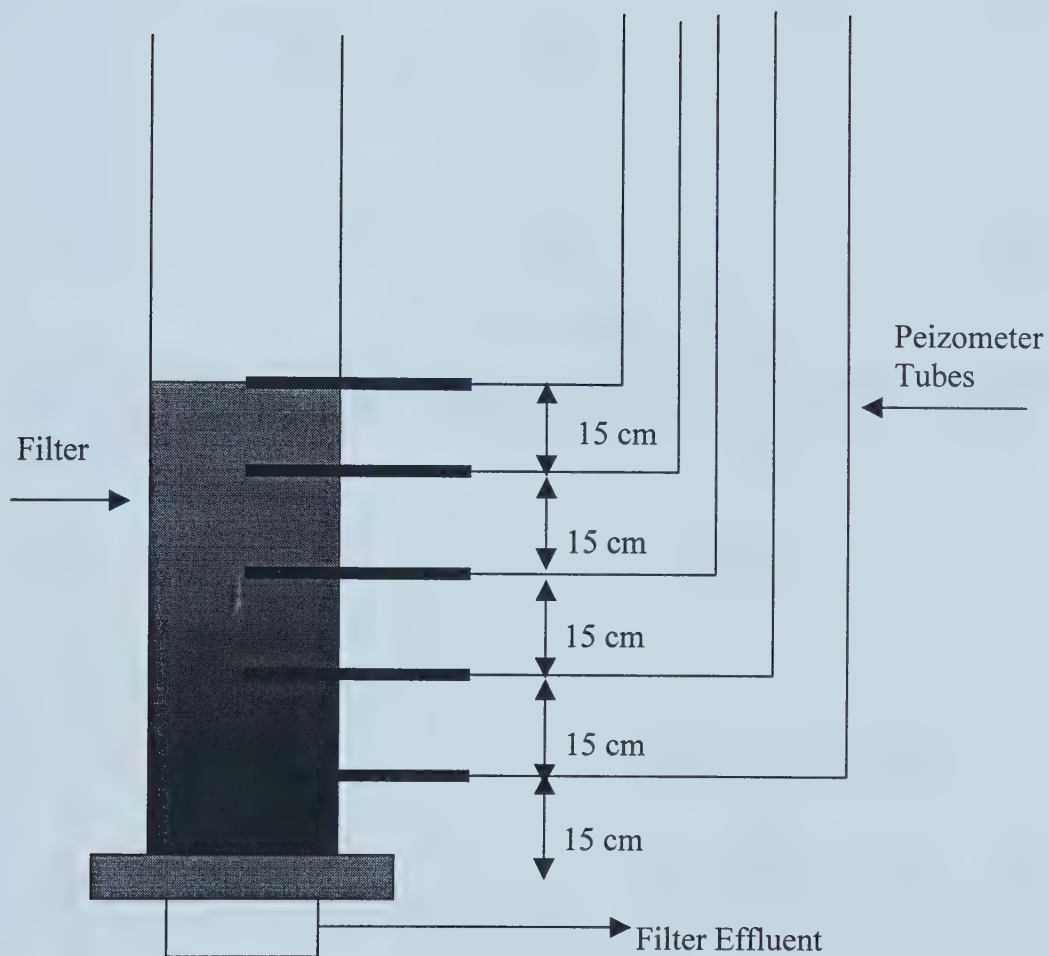
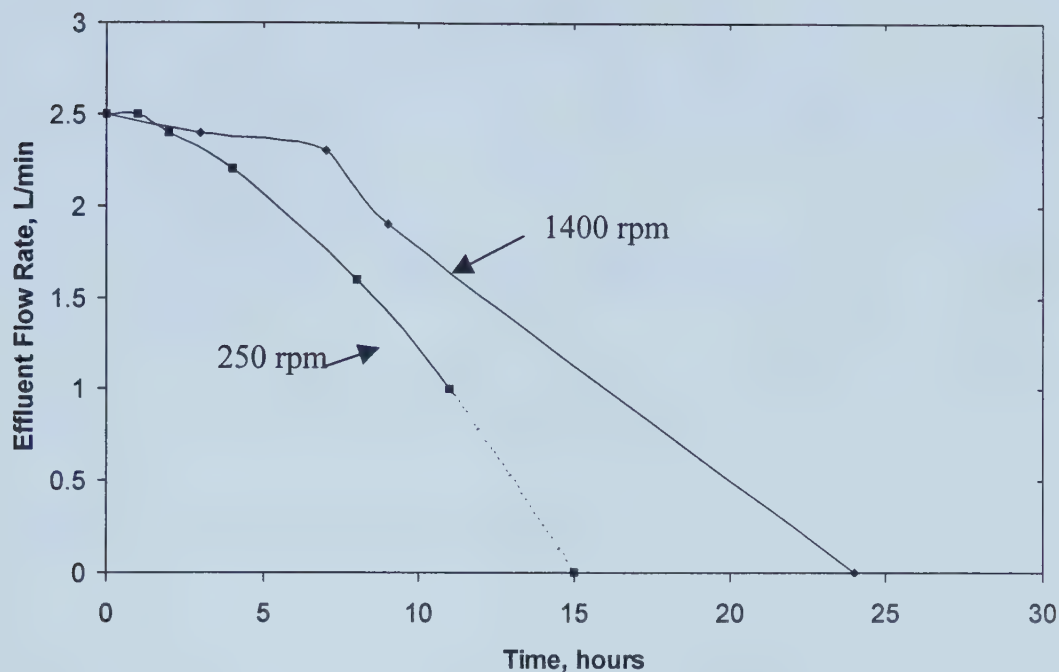**Figure 2.6. Schematic of Piezometer Locations on Sand Filters**

Figure 2.7. Effect of Mixing Intensity on Effluent Flow Rate for Pol-E-Z-652 Polymer at a Concentration of 0.04 mg/ml Using a 5 cm Diameter Paddle Impeller.
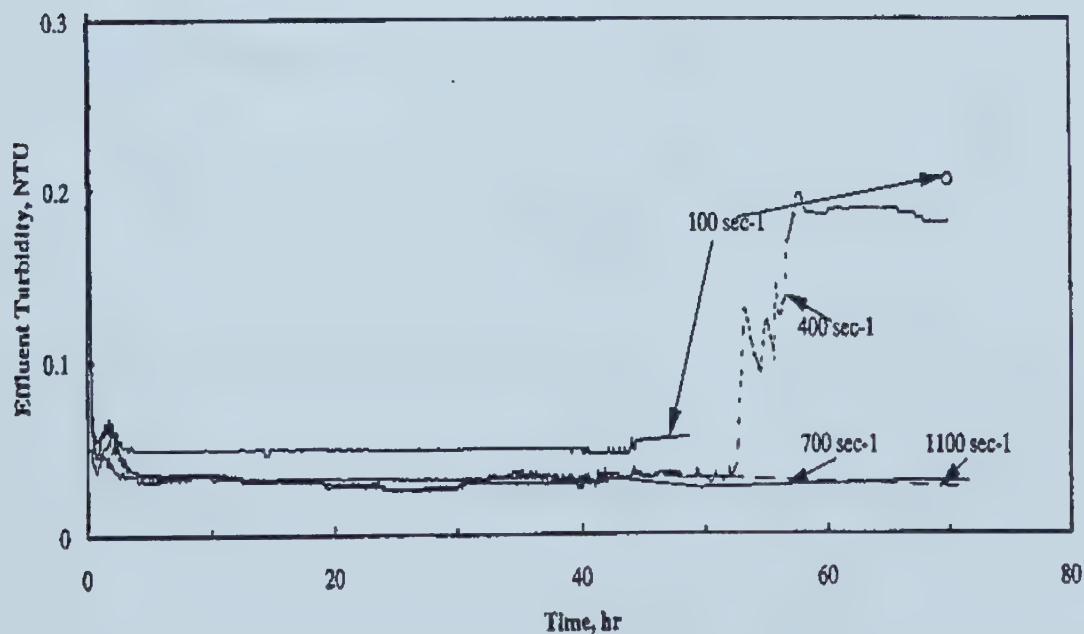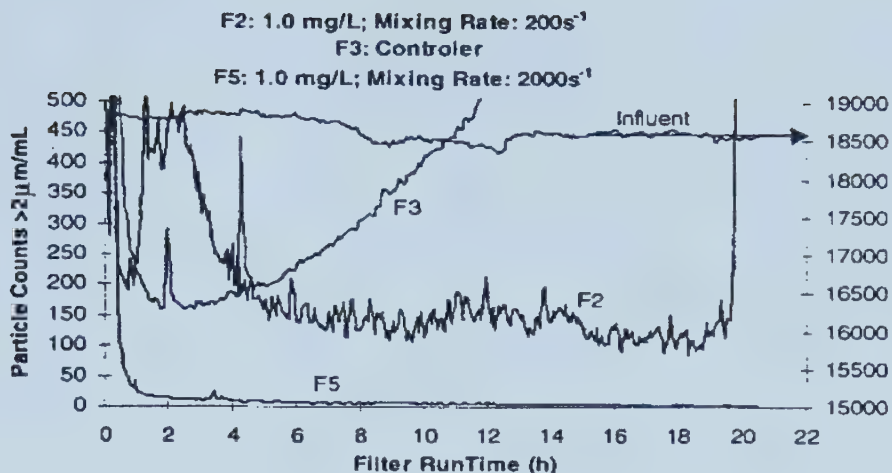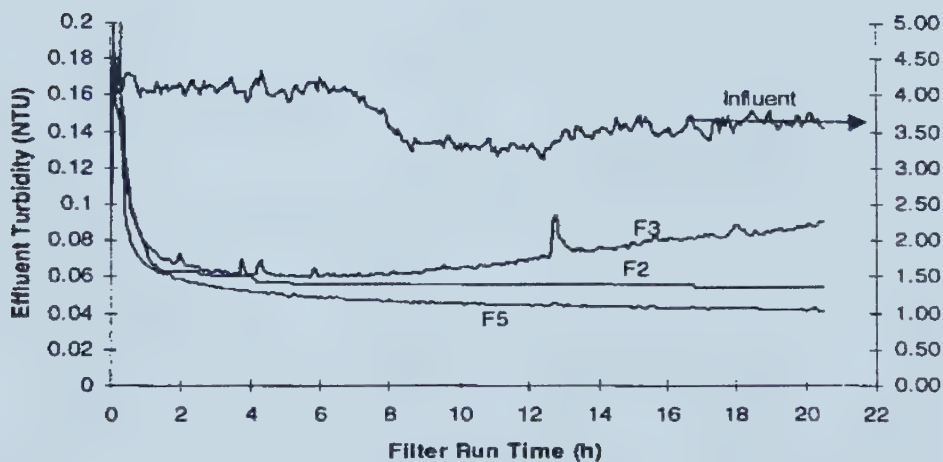

Figure 2.8. Effects of Mixing Intensity on Polymer Aided Filtration (Zhu *et al.*, 1996).

(a) Effluent Particle Counts *vs* Filter Run Time

(b): Effluent Turbidity vs Filter Run Time

Figure 2.9. Mixing Intensity Test Using Nalcolyte 8100 Polymer (Li, 2000)

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F2: 0.04 mg/L; Mixing Rate: 200s⁻¹
F3: Control
F5: 0.04 mg/L; Mixing Rate: 2000s⁻¹

(a) Effluent Particle Counts *vs* Filter Run Time

(b): Effluent Turbidity vs Filter Run Time

Figure 2.10 Mixing Intensity Test Using POL EZ 652 Polymer (Li, 2000)
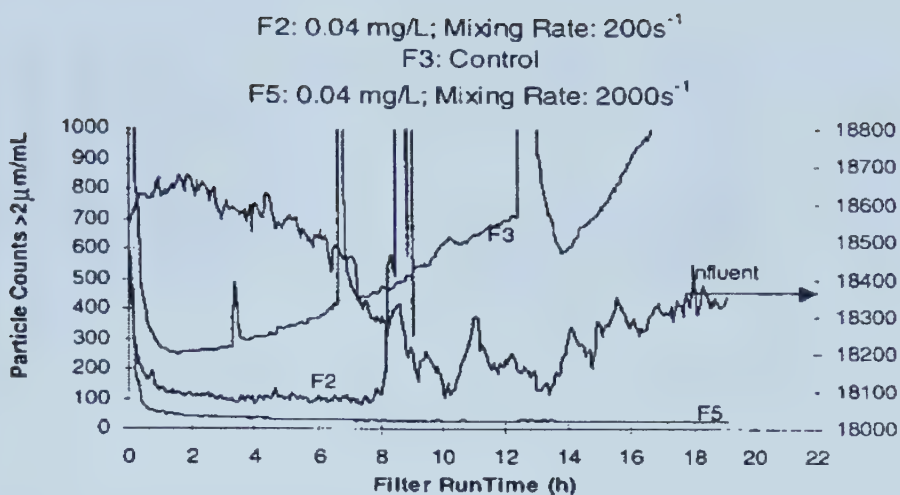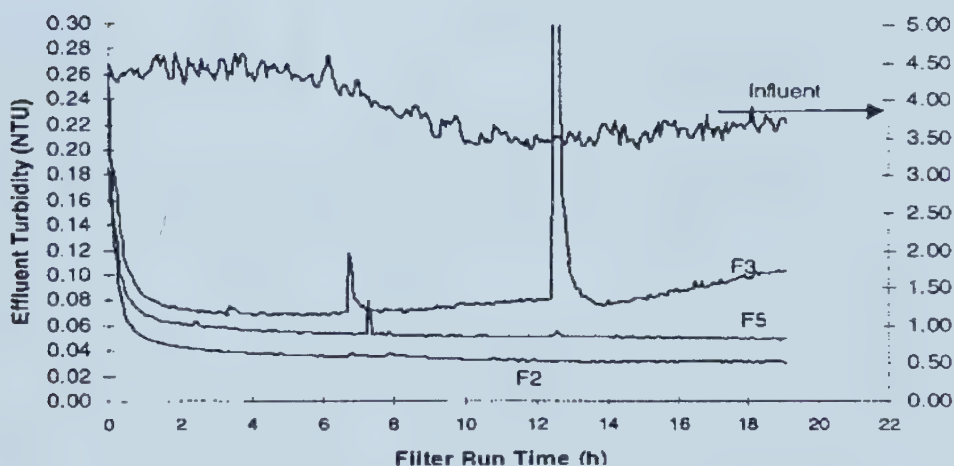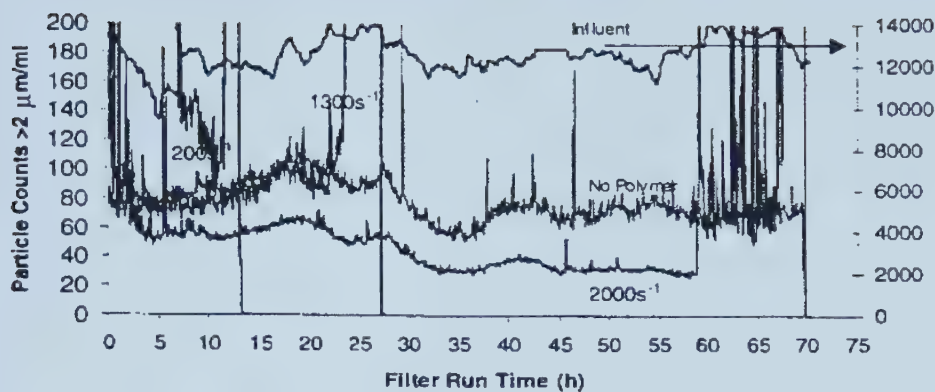
(a) Effluent Particle Counts *vs* Filter Run Time
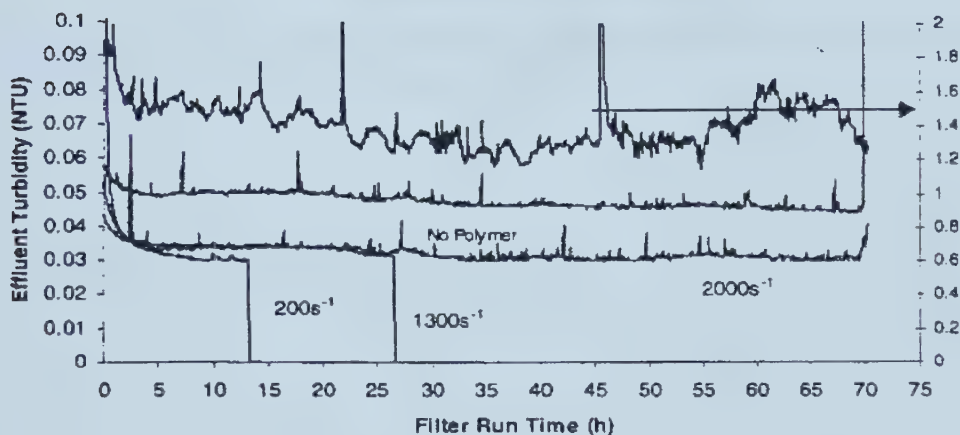
(b): Effluent Turbidity vs Filter Run Time

Figure 2.11. Mixing Intensity Test Using LT 24 Polymer (0.01 mg/ml) (Li, 2000)
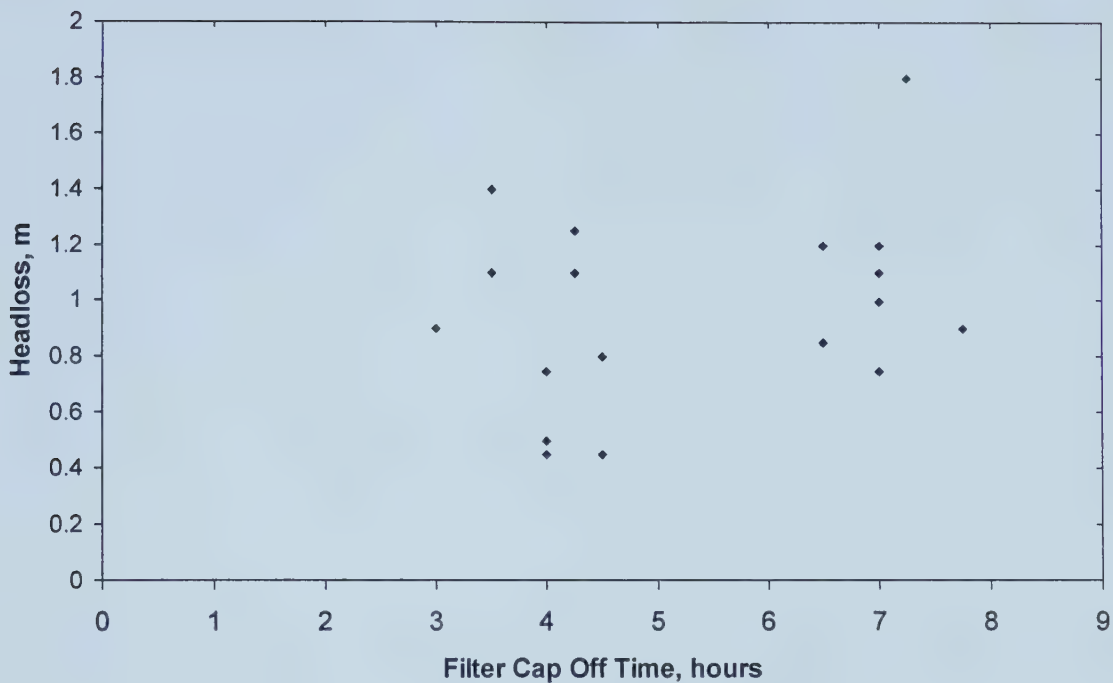
Figure 2.12. Comparison of Total Headloss across the Filter to Filter Cap Off Time for Various Impeller Types and Sizes
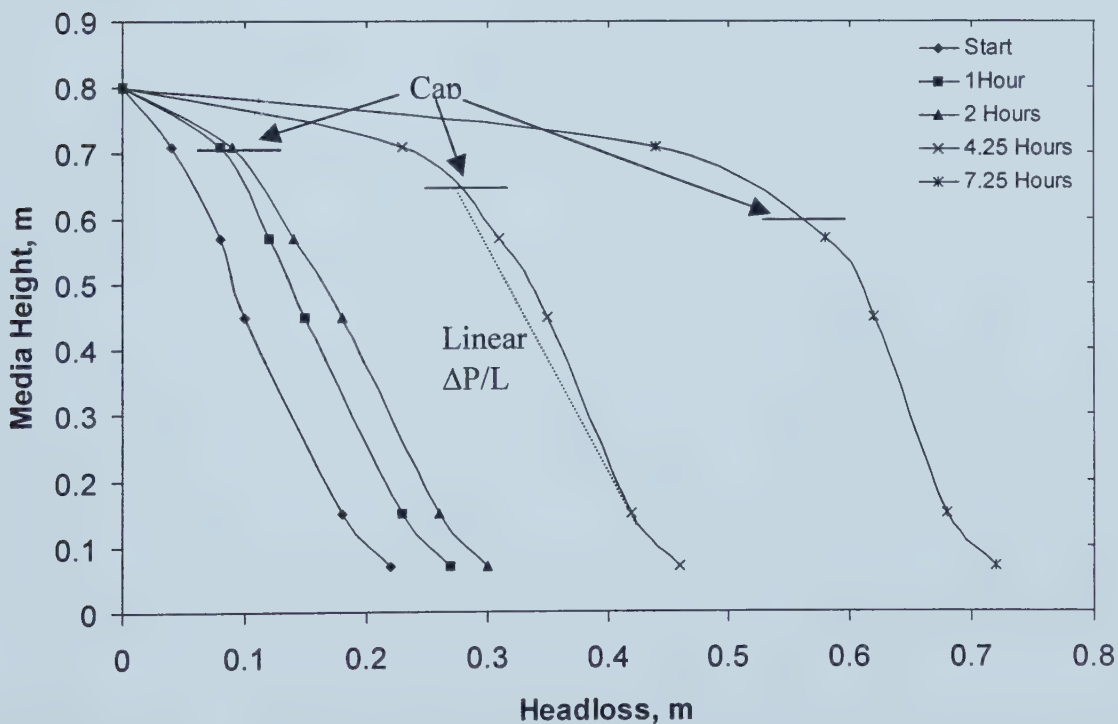
Figure 2.13. Headloss Profile along Filter Media for 3.8 cm Diameter Paddle Impeller at 250 rpm using Pol-E-Z-652 Polymer Concentration of 0.04 mg/ml.
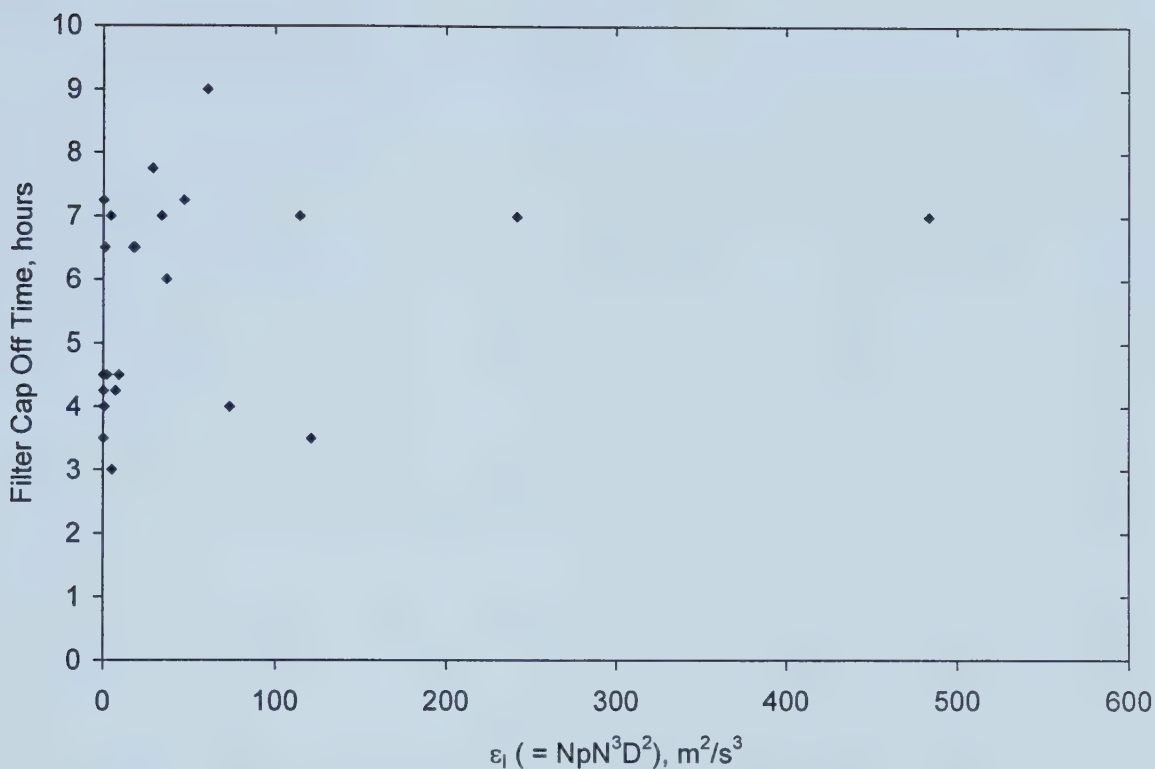
Figure 2.14. Comparison of Filter Cap Off Time to Energy Dissipation at the Impeller .
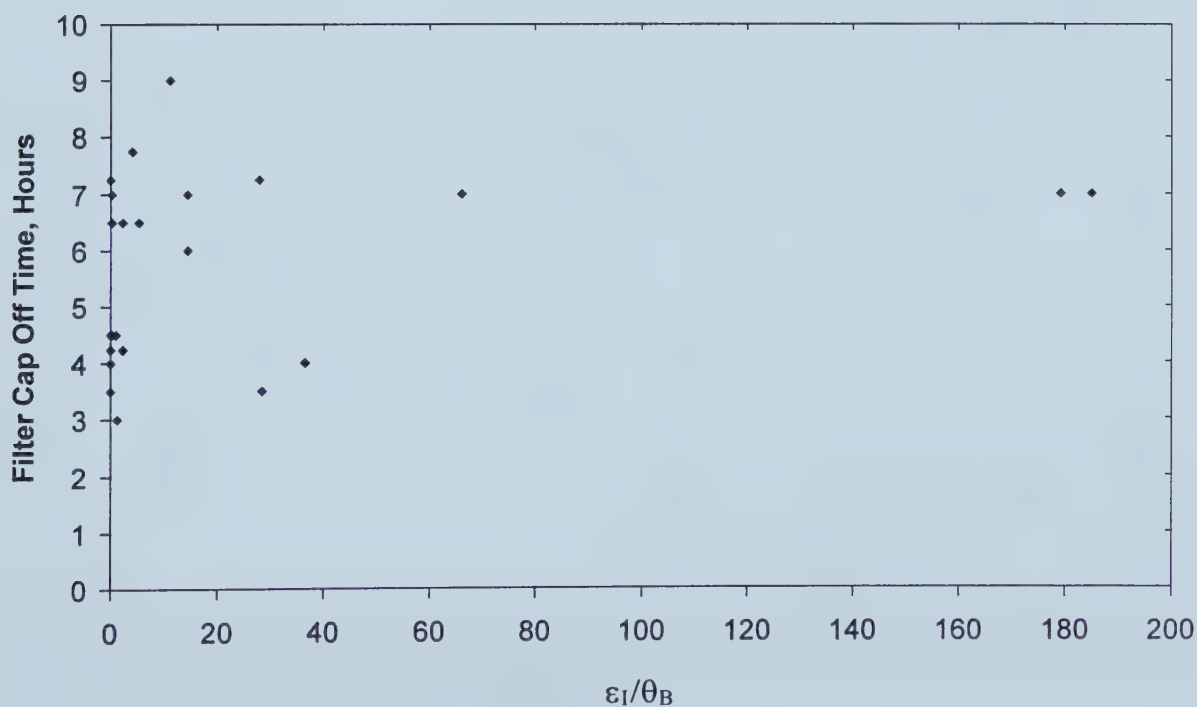
Figure 2.15. Comparison of Filter Cap off Time to Ratio of Energy Dissipation at the Impeller to Blend Time.
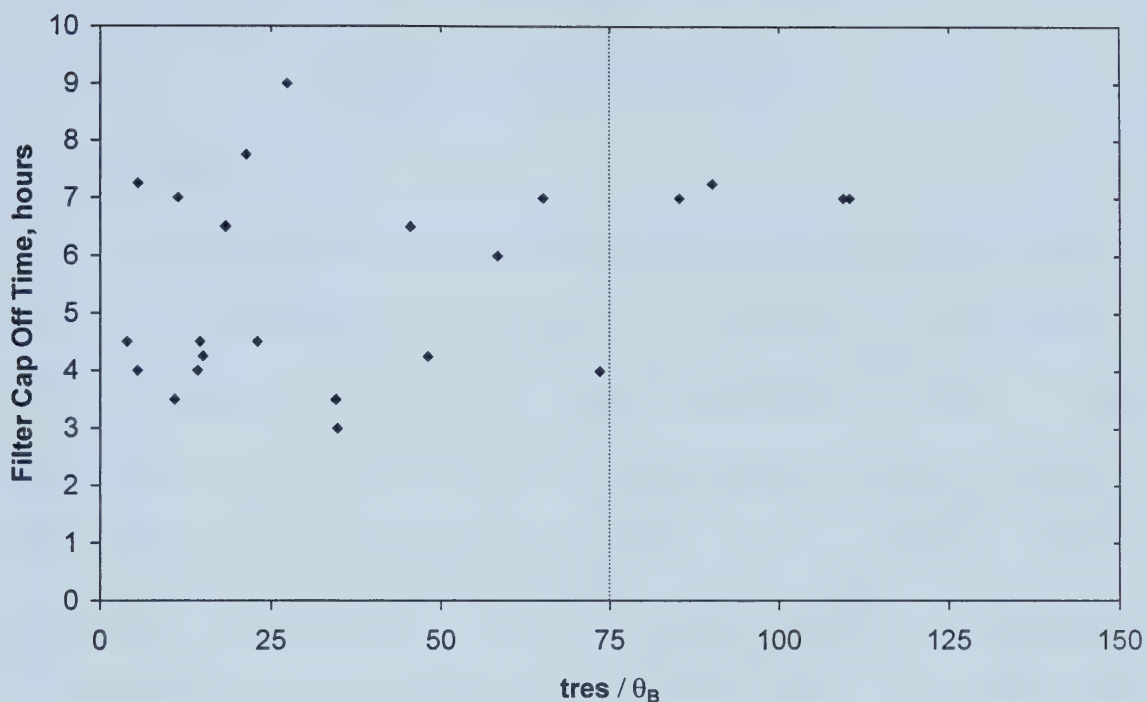
Figure 2.16 Comparison of Filter Cap Off Time to Ratio of Mean Residence Time of the Tank to Blend Time
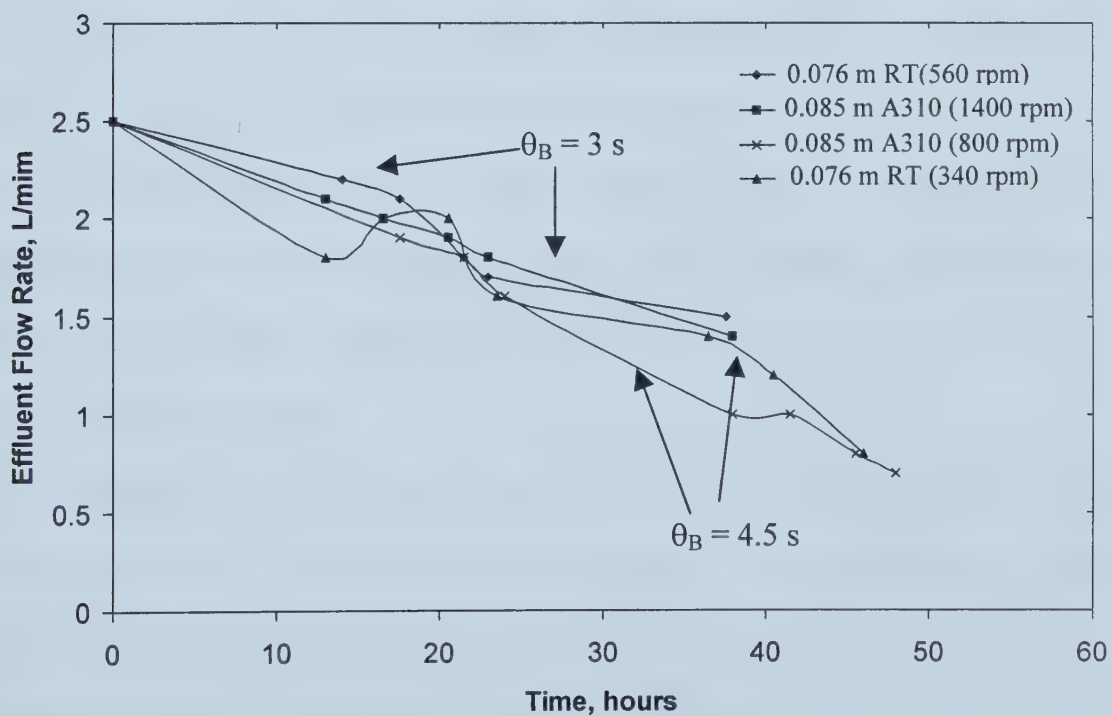
Figure 2.17. Significance of Radial and Axial Impellers at Similar Blend Times on Effluent Flow Rate for Percol LT7996 Polymer concentration of 0.25 mg/ml using a 5 cm diameter Paddle Impeller

Chapter 3

Physicochemical Effects

3.0 Introduction

One of the main factors in determining the type of filter aid polymer used is the cost. To conserve costs and avoid wasting polymer, the optimum polymer concentration needs to be determined. In evaluating the optimal concentration, the filter run length and the water quality are monitored. Most polymer concentrations will result in good effluent quality, therefore, the filter run length is used to evaluate the polymer performance. At low polymer concentrations, the time required for conditioning of the filter media increases as more time is required for polymer to accumulate in the filter before significant particle removal occurs. At high polymer concentrations, the run time of the filter is significantly shorter as the polymer accumulates in the filter at a faster rate. This will result in the filtrate quality marginally increasing, and a higher rate of headloss development in the filters. This rapid headloss development may lead to an early turbidity breakthrough (AWWA, 1990). Therefore, to determine the optimal polymer dosage, the filter run length must be maximized and the water quality must be maintained.

The initial testing at the pilot plant used water from the clarifier basin as the influent water source. This water source was chosen as it contains relatively high amounts of solids, averaging between 12,000 and 16,000 particles per milliliter. The high amount of solids results in short filter runs enabling more tests to be performed in a given time period which was beneficial for the initial testing. However, the water treatment plant adds the filter aid polymer to the water coming from the stilling basin

before it enters the filters. This stilling basin is where chlorine is added to inactivate microorganisms. In order to determine the reproducibility of the results across different water sources, the experiments were repeated using the stilling basin water. The stilling basin water contains considerably fewer particles than the clarifier, averaging 2,000 to 3,000 particles per milliliter.

Regardless of the water source used in the testing, the interaction between the polymer and the filter media is still important for the capture of particles. When filter aid polymer is used, the attachment mechanism between the particles and the filter is strengthened leading to lower detachment rates of particles from the media. This means that the filters can be operated at a higher loading. The downside of the lower particle detachment rates is that polymer will remain on the filter media after backwashing. The residual polymer on the media may reduce the initial conditioning time required for the filter but over time, it will decrease the filter performance and may lead to a situation where the particles will no longer attach to the media.

While the polymer interaction with the filter is important for particle capture, the completeness of polymer dispersion will also directly affect this process. The first step in the polymer dispersion is the dilution of the vendor supplied polymer solution into the stock and working solutions. The initial dilution of the polymer should result in a dispersed system. The concept of a completely dispersed system is based on the determination that dispersion has been achieved in all parts of the container and is usually confirmed by visual inspection. Even though the solution looks dispersed to the naked eye, it may in fact be far from a completely dispersed system at a microscopic or molecular scale. If the initial dilution and mixing of the polymer do

not produce a completely uniform solution it may be a result of polymer properties such as surface tension, viscosity, solubility and miscibility. These properties determine the level of dispersion and mixing time required to achieve equilibrium conditions. The intrinsic viscosity of the polymer solution determines the configuration of polymer in the solution. However, due to insufficient information on the vendor supplied polymer solutions the intrinsic viscosity was not determined. Surface tension determines the resistance of the polymer drops to deformation and breakage. Determining the surface tension for the polymer-water system was beyond the scope of this study of miscible liquids and was not investigated. However, the role of surface tension is important factor in the mixing and dispersion of immiscible liquids.

Any viscosity differences between the polymer solution and water will affect the dispersion kinetics. To completely mix similar viscosity liquids, a short mixing time is required as the viscous forces are easily overcome by the inertial forces imparted by the agitator. For liquid systems with large viscosity differences, there will be more resistance to shear, elongation and mixing.

Two polymer properties of interest in this study are solubility and miscibility. It is beneficial to determine the solubility and miscibility of the polymer-water system both at equilibrium and at short times. Solubility dictates whether the polymer will dissolve in the water while miscibility dictates the ease with which the polymer will be dispersed into the water. Many polymers are water soluble at normal temperatures but will precipitate out of solution when cooled or heated. The polymer may also be soluble up to a certain temperature or concentration of consolute and insoluble

beyond that point (Molyneux, 1983). The cloud point of a polymer-water system gives the solubility of the system at equilibrium for various temperatures.

A polymer-water system may be thermodynamically soluble, as defined by the Gibbs Free energy of mixing, but not kinetically miscible. Thermodynamics dictates what the equilibrium state for the system will be but it is often the kinetics that determine if the equilibrium state will be reached and how fast (Schwoyer, 1981). The kinetics of the polymer dispersion at short times can be used to indicate how fast this equilibrium condition will be reached. Dispersion is the process by which a minor phase is broken down into a greater number of smaller particles. The size of the dispersed drops is a function of the level of agitation and a certain number of impeller revolutions is required to produce "fully mixed" conditions. A miscible polymer will be dispersed almost instantaneously upon mixing. An immiscible polymer will require more time to reach homogeneous conditions: for example, Lam *et al.* (1996) found that drops continue to break apart and evolve towards smaller drop sizes over an experimental time of up to 10 hours while blend times in completely miscible systems are of the order of seconds. For a partially miscible polymer, the polymer drops must be reduced to a size where molecular diffusion dominates. However, it may take considerable time to reach this drop size and even then molecular diffusion may be a slow process.

3.1 Study Outline

The following chapter is divided into six sections corresponding to six hypotheses that were tested in this study: effect of polymer dosage, effect of water sources, polymer interaction with the filter media, effect of viscosity, polymer solubility under

experimental conditions and miscibility at short times. Each section contains the experimental design, experimental measures, results and conclusions.

3.1.1 Effect of Polymer Dosage on Filter Performance

The first section examines the hypothesis that polymer dosage affects the filter performance. This set of experiments was performed at the pilot plant and tested the Pol-E-Z-652 polymer at concentrations of 0.02 and 0.08 mg/ml. Both concentrations were subject to mixing intensities of 250 (G = 125 s^{-1}) and 1400 rpm (G = 1245 s^{-1}). The mixer was equipped with a 0.05 m diameter paddle impeller. The water source for this set of experiments was the clarifier basin.

The results of using the various polymer concentrations are given in Figures 3.1a and 3.1b. These figures also include data for the 0.04 mg/ml polymer concentration for comparison. These results indicate that as the polymer concentration is increased, the filter run time decreases. A direct comparison of the two different mixing conditions shows that there is an effect of mixing and that increasing the mixing intensity results in longer filter run times for low concentrations. These results are consistent with the results found in Chapter 2; however, if the concentration of the polymer is increased to a level of 0.08 mg/ml, even rapid mixing has no effect.

When using polymers as filter aids, there is a maximum concentration beyond which any increase in polymer concentration will start to hinder the filter performance. If the polymer saturates the system, excess polymer will coat the top of the filter and block the flow at the surface of the filter. This blockade results in faster headloss development and shorter filter run times. At high polymer concentrations,

brush-like layers can form on the particles which leads to steric stabilization rendering the surface of the particle unable to adsorb to other particles or to the filter media (Probstein, 1989). With steric stabilization, the particle surface becomes covered through adsorption or chemical reaction, usually by long chain molecules, and results in the repulsion of other particles. At low polymer concentrations, the probability of polymer-particle contact is significantly reduced as there are fewer polymer molecules in the system. At a low polymer concentration more time is required to accumulate polymer in the filter bed before restriction of flow occurs and the time required for conditioning the filter increases. The results from these experiments also adds insight as to why no effect of mixing was seen when using the various impeller types. If the polymer concentration used for the initial testing was too high, no effect of mixing would be observed.

3.1.2. Effect of Water Source on Filter Performance

The second section tests the hypothesis that the water source used in the pilot plant will impact the filter performance. Since the full scale plant adds the filter aid polymer to the water from the stilling basin, previous mixing experiments were repeated using the stilling basin water. The Pol-E-Z-652 polymer at concentrations of 0.02, 0.04 and 0.08 mg/ml were subject to the mixing intensities of 250 ($G = 125$ s^{-1}) and 1400 rpm ($G = 1245$ s^{-1}). For these experiments, the mixer was equipped with a 0.05 m diameter paddle impeller.

Figures 3.2a and 3.2b show the results for the experiments using water from the stilling basin. These results show that mixing becomes a secondary factor when stilling basin water is used. A direct comparison of mixing intensities showed that an

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effect of mixing is only observed at a polymer concentration of 0.08 mg/ml. In this set of tests, increasing the mixing does result in an increase in filter run time for the high polymer concentration where the filter run time increased from 96 hours to more than 120 hours. No effect of mixing is seen at the other polymer concentrations suggesting that mixing is not the dominant factor. This is opposite to what was found when using water from the clarifier basin. Further comparison of the results from the two different water sources shows that one similar trend is found between them. This trend is that regardless of the mixing intensity, as the concentration of the polymer increases, the filter performance decreases. However, when stilling basin water is used, this trend is not as pronounced. Therefore, it can be concluded that the water source has a direct impact on the filter performance.

In comparing the results obtained from the two water sources, another significant difference is seen. Tests using the clarifier water resulted in filter runs lasting 24 hours compared to filter runs of 120 hours when using the stilling basin water. There are several explanations for the difference in filter run lengths between water sources. First, lower influent particle counts are found in the stilling basin water than in the clarifier water. Therefore, fewer particles are passing through the filters at any given time. When using water from the stilling basin, fewer particles means that more time is required for particles to accumulate before pore restriction becomes a problem. A higher turbidity loading will reduce the filter run time and increase the chance of a breakthrough (Tarquin *et al.*, 1998).

The second significant difference between the two water sources is that the stilling basin contains chlorine. Chlorine is a strong oxidant which readily reacts with

organic material in the water, potentially changing its molecular size and surface properties. The polymer used for this study is an organic polymer and it is speculated that the chlorine reacts with the polymer in some way, though the exact mechanism remains unknown. According to Glaze and Peyton (1977), chlorine can be used as an oxidant to break up larger molecules into smaller molecules which are less likely to be captured in the filter. Compounds in the water may also react with the chlorine to form chlorine derivatives that act as oxidants and contribute to the longer filter run times (Ingols, 1961). Finally, chlorine may change the surface properties of a microorganism and alter certain compounds of organic matter to form substitute compounds by changing the properties of the material (CWWA, 1993). In summary, chlorine can alter the surface properties of particles such that the efficiency with which the polymer adheres to particles and filter media is affected.

3.1.3. Polymer Interaction with Filter Media

The results from the previous two sections prompted questions about the interaction of the polymer and the filter media, as it is speculated that the polymer attachment mechanism is affected by the water sources used. It is hypothesized that the polymer is coating the filter media reducing its effectiveness. To determine this, samples were taken from the water treatment plant filters and from all three filters in the pilot plant, after the media had been backwashed, and were examined under a scanning electron microscope.

A scanning electron microscope (SEM) has unique abilities for analyzing surfaces as it has an extensive magnification range and high depth of field that permits higher magnification without loss of detail. It also maintains the three

dimensional appearance of the textured surface (Gabriel, 1985). An SEM uses electrons for image formation as the shorter wavelength of electrons is capable of generating higher resolution information. To examine the surface of the filter media, a Hitachi S-2700 model scanning electron microscope was used. The microscope used the digital imaging system PGT IMIX manufactured by Princeton Gamma Tech.

There are three systems in the SEM used to acquire images: illuminating/imaging, information and display. The illuminating/imaging system is comprised of an electron gun that produces the electron beam and directs it into the sample chamber. This system has several magnetic lenses that serve to produce a collimating beam of electrons so that it can be focused on the sample. The samples were coated with gold dust so they could be detected by the SEM as sand is not a conductive medium. The sample chamber is operated under vacuum to remove residual gas molecules so that the electron beam is not scattered. When the sample is bombarded by electrons, it releases a variety of data signals which are recognized and analyzed by a series of detectors in the information system. The information system collects the data and transfers it to the display system. The display system displays the images on the screen of a cathode ray tube. Permanent records are obtained from the SEM by photographing the cathode ray tube (Gabriel, 1985).

It has been speculated that the polymer increases attachment of particles to the filter media. According to Fettig *et al.* (1991), the favorable effect of the polymer improving the attachment of particles on the filter media results in lower detachment rates at higher loading. While this reduction in detachment is beneficial in particle capture, it counteracts the cleaning process and may result in polymer being retained

on the filter media. Figure 3.3a shows that the polymer used in the water treatment plant has completely coated the filter media. This image shows that the media has been well conditioned by the polymer. In contrast, Figure 3.3b shows a sample of the pilot plant media that has very little polymer residual on it. In the right hand corner, near the center, a jagged, clean crystal on the media particle can be seen. This represents what a clean piece of media looks like under the SEM. Figure 3.3c shows a sample of pilot plant media where polymer deposits have started to form. The left side of the image shows the polymer deposits on the media. The right side of this image shows that the area adjacent is relatively free of polymer deposits. These two figures are in sharp contrast to Figure 3.3d which shows the water treatment plant media at the same magnification as the pilot plant media images. This shows the significant amount of coating that has occurred. The reason the media in the pilot plant does not have the same degree of polymer coating is that it has not been in use as long as the water treatment plant media. The pilot plant media was replaced in May of 2000 with the well conditioned media from the water treatment plant to limit variability between the pilot plant filters.

The increase in the attachment strength means it is difficult to detach particles from the filter media. Therefore, the normal backwash procedures may not be adequate to detach all of the polymer from the media. The residual polymer on the media helps decrease the time required for the initial conditioning of the filter, but may also contribute to the decline of the filter performance over time. The filter media may eventually become permanently coated with a thin polymer layer making the filter media less effective.

3.1.4 Effect of Viscosity on Mixing of Polymer Solution

The fourth section examines the hypothesis that the viscosity of the polymer solution influences the time required to completely disperse the polymer in the mixing tank. To determine if viscosity of the working polymer solutions influenced the mixing, the viscosity of the Pol-E-Z-652 and Percol LT7996 polymers at concentrations of 0.096 and 0.60 mg/ml, respectively, was measured using a capillary viscometer. The polymer solutions were placed in a size 100 calibrated Fenske viscometer. The time for the polymer solution to flow through the capillary was recorded and the viscosity of the polymer solutions was determined using the viscometer calibration equation and time measurement as shown in Appendix III.

When the two vendor supplied polymer solutions were compared, it was observed that the Pol-E-Z-652 was more viscous than the LT7996 polymer. The Pol-E-Z-652 working solution of 0.096 mg/ml had a viscosity of 1.08 cp and the LT7996 working solution of 0.60 mg/ml had a viscosity of 1.16 cp. Both viscosities are similar to the viscosity of water at 20°C. It was concluded that the viscosity of the polymer solution does not significantly affect the mixing of the polymers as mixing of similar viscosity fluids requires short mixing times.

3.1.5. Solubility of Polymer at Experimental Conditions

The fifth hypothesis is that the polymer is insoluble under experimental conditions. To evaluate the solubility of the polymer, the cloud point temperature for various concentrations of the Pol-E-Z-652 polymer was determined. The cloud point temperature was determined by agitating the polymer solution in a water bath, at a fixed temperature, for 24 hours. A spectrometer was used to record the increase in the

transmission of light through the solution after 24 hours. The cloud point was determined for polymer concentrations of 0.08, 0.096, 0.192 and 1 mg/ml. Concentrations below 0.08 mg/ml could not be tested due to limitations with spectrometer. The experiment was performed over a temperature range of 19 to 28°C.

The polymer solutions were prepared using the same procedure that was used in the pilot plant testing. A 50 ml sample of the polymer solution was placed in a 75 ml Erlenmeyer flask. The flask is secured into the clasps in the waterbath at the desired temperature. The spectrometer probe used for this testing has a diameter of 5 mm and is 10 mm in length. The probe, which is attached to the sampling optics and contains a collimating lens, is placed in the flask to record the initial transmission. The probe is initially referenced using water filtered by reverse osmosis. After the initial transmission reading is taken, the flask is sealed with a rubber stopper to ensure no liquid is lost during agitation. The waterbath is set to rotate at a speed of 225 rpm to circulate all of the liquid in the flask. After the 24 hour period, the transmission through the solution is measured and compared to the initial transmission measurement. In addition to the flasks prepared for the waterbath, a reference sample of the same polymer solution was placed in a flask, sealed with a rubber stopper and left on the lab bench, unagitated, for 24 hours. These samples were used as a visual comparison to the samples in the water bath.

The spectrometer used was the S2000 Miniature Fiber Optic Spectrometer which is a high sensitivity UV-VIS shortwave NIR spectrometer. There are several components to the spectrometer including the A/D converter, light source, sampling optics and OOI Base operating software. The sampling optics, which are connected

to the probe, are placed in the polymer solution. The light source supplies light through the illumination fiber of the sampling optics into the sample. After the light interacts with the sample, the collimating lens converts the divergent light beams into a parallel beam which is then collected and transmitted through the read fiber of the sampling optics. This data is then sent to the A/D converter which transforms the analog data into digital information that is passed to the software (Ocean Optics, 2001). For this set of tests, the transmission mode was used. The transmission mode is used to show the portion of light reflected from a sample. Transmission is the percent of energy passing through a system relative to the amount that passes through the reference. The equation used by the software to calculate the transmission is given in Appendix IV.

The cloud point data for the Pol-E-Z-652 indicates a general trend over a range of polymer concentrations as shown in Figure 3.4. For all of the samples tested, the transmission of light through the sample increased over the 24 hour time period and across the entire temperature range tested. However, the high concentration polymer solution (1 mg/ml) did not become completely clear which indicates that this concentration remains below the cloud point temperature. The long equilibrium time required indicates that these solutions have some resistance to dissolution at these conditions. The cloud point data indicates the existence of two temperatures where a significant increase in transmission is seen. These temperatures are at 24 and 28°C. Even though the cloud point was determined for the temperature range of 19 to 28°C, most of these temperatures are located outside the range of the operating temperatures for the water treatment plant. In the plant, the water

temperature can vary from 0°C in the winter to 20°C in the summer. The cloud point data is still significant as it indicates that the polymer is completely soluble at experimental conditions.

3.1.6. Miscibility of Polymer at Short Times

The final section examines the hypothesis that the polymer is immiscible in water at short times. To test this hypothesis, the initial dilution of the Pol-E-Z-652 polymer into working solutions was investigated and the dispersion kinetics were evaluated. To examine the dilution of the polymer into working solutions, various concentrations were examined under an optical microscope. The polymer concentrations used in this section were 0.02, 0.04, 0.048, 0.08, 0.096, 0.192 and 1 mg/ml. All solutions were prepared using the same procedure used for the pilot plant experiments. A sample of the polymer solution was placed on the microscope slide and covered by a slide cover. The sample was examined under a optical microscope at a magnification of 100 times. The microscope was attached to a digital camera.

When these solutions were examined under a microscope, drops were clearly visible, as shown in Figure 3.5a. The stock solution is the first dilution of the polymer in water and indicates that the polymer was not completely miscible at the dilution conditions. A system similar to a liquid-liquid dispersion exists. The Pol-E-Z-652 polymer is an emulsion and when diluted should invert and release the polymer from the emulsion (pers. corr., B. Prud'homme, 2001). The components of the polymer emulsion are unknown making it difficult to be certain if inversion even occurs and, if so, at what rate. This makes it difficult to determine if the polymer is released from the emulsion at these conditions. Therefore, it is postulated that the drops seen in the

images are drops of the emulsion that still contain polymer indicating that the polymer is not uniformly dispersed under the dilution conditions. Due to limited access to the microscope, the average drop size of the polymer in the solutions could not be determined as a limited number of pictures were obtained. Even with the small sample size, a general trend in polymer size at the various concentrations can be seen as indicated in Figures 3.5b through 3.5d. The pictures of the polymer solutions indicate that as the polymer concentration decreased, the size of the polymer drops in the solution decreased. Figure 3.5b shows an example of the drop sizes that are found at a polymer concentration of 0.08 mg/ml. These drops are bigger than the ones seen in Figure 3.5c and 3.5d which represent polymer concentrations of 0.04 and 0.02 mg/ml, respectively. The smaller drop sizes may contain fewer polymer chains, resulting in more dispersion of the polymer throughout the container than the larger drops which may contain several polymer chains. The fewer polymer chains contained in the drop, the more likely the polymer will be dispersed under continued agitation. These images illustrate that the working polymer solution is not completely dispersed after the second dilution step which indicates that the polymer is not easily mixed into solution.

The dispersion kinetics were evaluated using a variable speed Lightnin motor with a maximum speed of 550 revolutions per minute, equipped with a 0.076 m diameter paddle impeller. The impeller was mounted in the center of the tank at an off-bottom clearance of 0.025 m. The mixing tank is a Plexiglas cylindrical tank with an inner diameter of 0.24 m and a height of 0.37 m. The tank is equipped with four baffles, each having a width of 0.0225 m and a height of 0.25 m, equally spaced

around the periphery of the tank. The liquid height in the tank was equal to the baffle height resulting in a liquid volume of 11.3 liters.

For this set of experiments, the dispersion kinetics for three concentrations of the Pol-E-Z-652 polymer were determined: 0.02, 0.04 and 0.08 mg/ml. The polymer stock solution was prepared using the same method as the pilot plant experiments. The amount of stock solution required to achieve the necessary concentration in the 11.3 liter tank was calculated using the formula in Appendix II. For this set of experiments, tap water was used as the water source. The polymer solutions were subjected to two mixing intensities: 360 (θ_B = 6.0 s and G = 370 s^{-1}) and 500 rpm (θ_B = 4.3 s and G = 600 s^{-1}). In addition to varying the mixing intensity, the injection point of the polymer was also varied. The polymer was injected at the top of the tank and near the impeller.

To evaluate the dispersion kinetics, the turbidity of the solution was monitored using a bench top turbidimeter. Samples were taken from the tank at five minute intervals for the first hour and then every half hour for the next two hours. Two different samples were obtained at each time interval using a pipette: one from the top of the tank and one near the impeller. The bench top turbidimeter operates under the same principle as the on-line turbidimeters described in Chapter 2, with the exception that the water sample is not continuously fed through the turbidimeter. The sample container containing the polymer solution is placed in the sample chamber and a tungsten-filament lamp focuses and passes light through the water sample. The light scattered by the sample is detected by the various detectors in the turbidimeter. The transmitted and forward scatter detectors receive light that passes through the sample.

The back scatter detector measures the light that is reflected back to the light source while the 90° scatter detector receives light that scattered at a right angle to the light beam. The data from all of these detectors is then incorporated into the turbidity measurement (Hammer and Hammer, 1996).

In evaluating the dispersion kinetics, the turbidity of the solution was measured. Turbidity is not a precise measurement, therefore, it is important to know how much variation there is between the data points. One way to determine the variation is to state the limits within which it may reasonably be asserted that the true value lies. The limits that are quoted are known as confidence limits and are the limits that the true value lies within for a given degree of confidence (Spendley, 1947). For evaluating the dispersion kinetics data, a 90% confidence interval was used. The equation for the confidence interval and a set of sample calculations are included in Appendix V.

The results from the dispersion kinetics experiments indicate that the feed point of the polymer has an effect. The effect of feed point is more important at the higher polymer concentrations and Figure 3.6a shows the results for the 0.04 mg/ml polymer concentration. The results indicate that for effective mixing of the polymer to occur, the polymer feed should be placed near the impeller where the highest level of turbulence occurs. If the polymer is fed at another point in the tank, it is harder to break up the initial polymer drops as there is less possibility of large amounts of polymer entering the impeller zone. When the polymer is fed at the top of the tank, there is no difference in the dispersion kinetics regardless of impeller speed as shown in Figure 3.6b for a polymer concentration of 0.02 mg/ml. When the polymer is

injected at the top of the tank, immediately after injection, the polymer begins to "sink" deeper into the tank. When the impeller is started, the polymer is no longer at the top of the tank and may be in the quiescent zone in the tank. The polymer may not be pulled into the fluid circulation in the tank and get cycled to the impeller zone. If the polymer is not cycled through the impeller zone, no breakage will occur. When injecting the polymer at the impeller, the polymer is dispersed quickly when the impeller starts to rotate. This results in a large number of polymer drops being immediately reduced and dispersed. To further examine the dispersion kinetics, only the impeller feed point data was used as the initial polymer dispersion is critical to the water treatment plant.

According to the turbidity data for the 0.02 mg/ml polymer concentration, when the polymer is fed at the impeller, the initial polymers drops are reduced in size and some of the drops are mixed into the water as seen in Figure 3.6c. In the first five minutes of mixing, the polymer is being significantly reduced in size as indicated by the rapid decline in the turbidity. After thirty minutes, the turbidity curve is still proceeding with a slight decline as some of the smaller polymer particle are being mixed on a molecular level by molecular diffusion. These results indicate that at these mixing conditions, the polymer is partially miscible. In the lab, the blend time in the tank was 6 seconds and if the polymer was completely miscible, the equilibrium turbidity would be reached almost instantaneously as indicated on Figure 3.6c. If the polymer was completely immisicble, the polymer particles would remain in solution and never be reduced below the maximum stable drop size. The polymer molecules would stay together indefinitely in the absence of molecular diffusion. The

maximum stable drop size is seen at equilibrium conditions which take considerable time to reach. The polymer immiscibility would be indicated with the turbidity measurements being initially reduced after which the measurements would remain constant with time as indicated on Figure 3.6c. However, the data shows that the turbidity measurement does reduce over time with the mixing indicating that some of the polymer is being mixed. This process is a very slow process and the time required to reach equilibrium is much longer than the residence times in the pilot plant and the mixing time in the tank. Therefore, the polymer is not always completely dispersed at pilot plant conditions. For the polymer concentration of 0.02 mg/ml, increasing the rotational speed of the impeller results in the turbidity of the solution decreasing at a faster rate. This is because the increase in turbulence in the tank results in smaller drop sizes being achieved faster. This increases the rate of molecular diffusion resulting in more dispersion of the polymer and lower turbidity. At dilute conditions, the polymer chains are coiled in the solution and are separate from each other and move independently. This results in regions that are denser in polymer segments than the overall concentration. In a good solvent, two polymer coils will behave like hard spheres and repel each other. Therefore, at this low concentration the only resistance to dispersion of the polymer is due to the size of the polymer coils. At this concentration, the higher mixing intensity results in equilibrium being reached quicker. However, this is not the case with the higher polymer concentrations. Figure 3.6d shows that the turbidity measurements for the polymer concentration of 0.04 mg/ml at the two rotational speed are not statistically different. The reason for this may be due to the polymer concentration. At concentrations slightly higher than those

for the dilute solution, a semi-dilute region occurs where the polymer chains begin to interact but are still distinct. If the concentration is increased further, the polymer coils start to overlap or interpenetrate (de Gennes, 1979). Solutions where this occurs may still have a low polymer fraction. The interpenetration of polymer coils adds resistance to dispersion as the mixing must untangle the individual polymer coils before reduction of individual chains can occur. The higher concentrations used in the study may have reached the overlap threshold where the polymer coils begin to be densely packed and add resistance to the mixing in the tank. The similar kinetic profile observed at the concentration of 0.04 mg/ml indicates that if overlap of the polymer occurs, no effect of mixing is observed. The entanglement of polymer chains also supports the results seen in Figure 3.6a where feeding the polymer at the impeller is more beneficial. To increase the rate of de-tanglement of the polymer coils, the coils must pass through the areas of high turbulence in the tank.

Figure 3.6c illustrates that long mixing times are required to reach equilibrium. These times are considerably longer than the residence time in the pilot plant mixing tank or water treatment plant. In the water treatment plant, it is the initial mixing of the polymer that is critical. From Chapter 2, it was concluded that the contents of the mixing time needs 75 blend times to achieve consistent results in the pilot plant. Using this data, it was determined that 75 blend times corresponds to the 50% mixed time in the kinetics experiments. This is a very long time for mixing and is not achievable under plant conditions. Therefore, the polymer that was used is only partially miscible at short times (approximately 30 minutes) even though it is completely soluble.

3.2 Conclusions

Based on the experimental results, the following conclusions can be drawn.

1. The dosage of the polymer has a direct effect on the filter performance as shown in Figures 3.1a and 3.1b. As the polymer dosage is increased, the headloss development in the filter increases resulting in short filter run times using water from the clarifier basin.

2. Using water from the stilling basin showed that mixing is a secondary factor. Therefore, it was concluded that both the polymer concentration and chlorination impact the filter runs as shown in Figures 3.2a and 3.2b.

3. Polymer deposits are found on the filter media indicating that the detachment of the polymer from the media is incomplete, leaving a coating on the media as shown in Figures 3.3a to 3.3d.

4. Viscosity does not adversely affect the mixing time required for homogeneous conditions as the polymer solutions have viscosities close to that of water at 20°C.

5. The initial dilution of the polymer does not result in a completely dispersed system as shown in Figures 3.5a to 3.5d.

6. To achieve the optimum dispersion of the polymer in the tank, the polymer should be fed near the impeller region as shown in Figure 3.6a. Feeding at the impeller increases the possibility of the polymer drops entering the impeller zone and being broken apart into smaller drops by the trailing vortices. The smaller drops increase the rate of molecular diffusion.

7. The polymer was found to be completely soluble under experimental conditions (after 24 hours), as indicated by the cloud point data given in Figure 3.4, but the

polymer is partially miscible at short mixing times (approximately 30 minutes) as illustrated in Figures 3.6a to 3.6d. This indicates that a significant amount of time is required to reach completely mixed conditions. These conditions are not obtained in the pilot plant as consistent results could only be obtained when at 75 blend times or 50% mixed time according to kinetics experiments. This resistance to dispersion could be a result of polymer coils overlapping making them more difficult to separate into single polymer chains.

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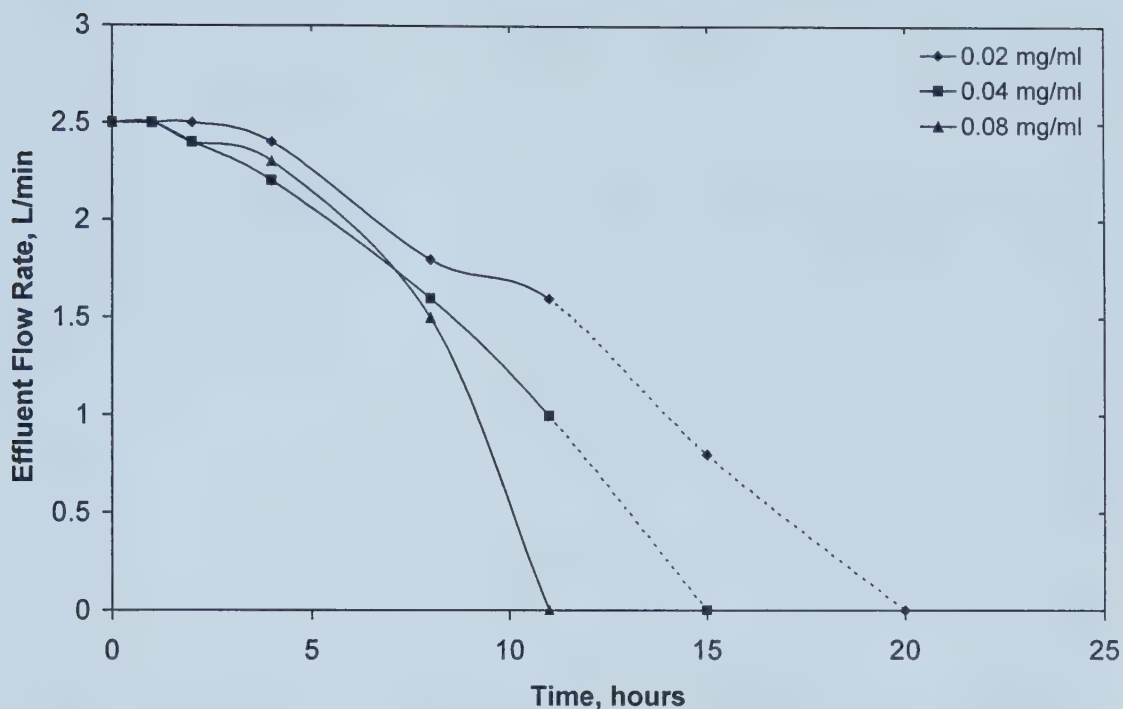
Figure 3.1a. Significance of Pol-E-Z-652 Polymer Concentration on Effluent Flow Rate at a Mixing Intensity of 250 rpm using a 5 cm Diameter Paddle Impeller and Clarifier Basin as Influent Water Source.
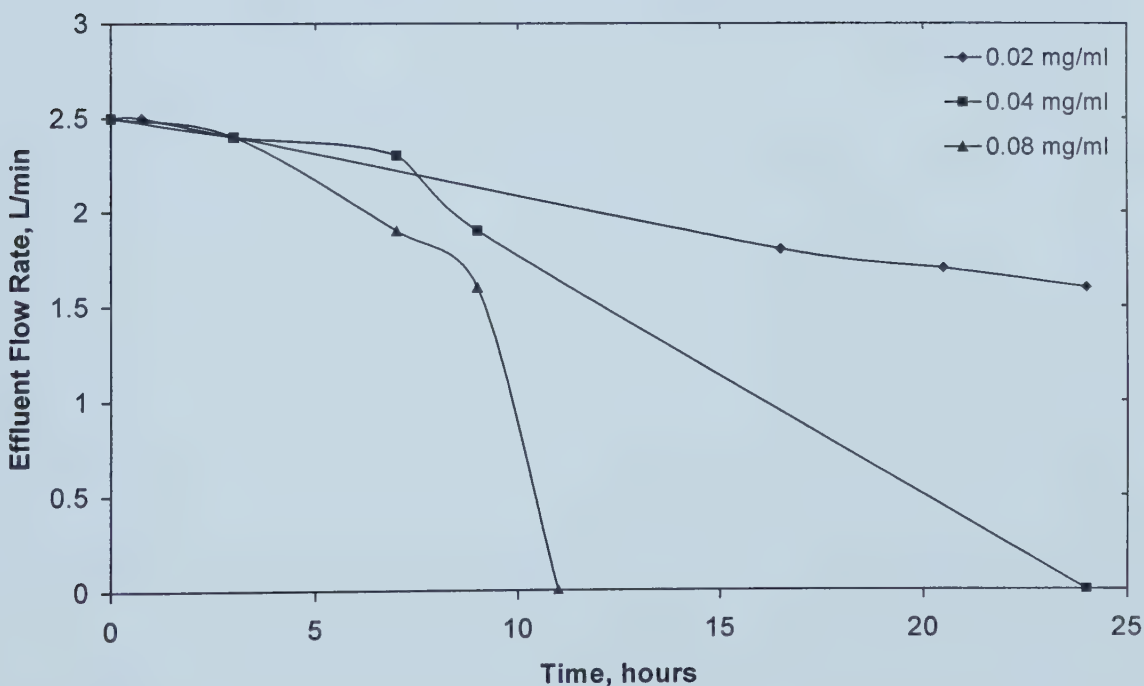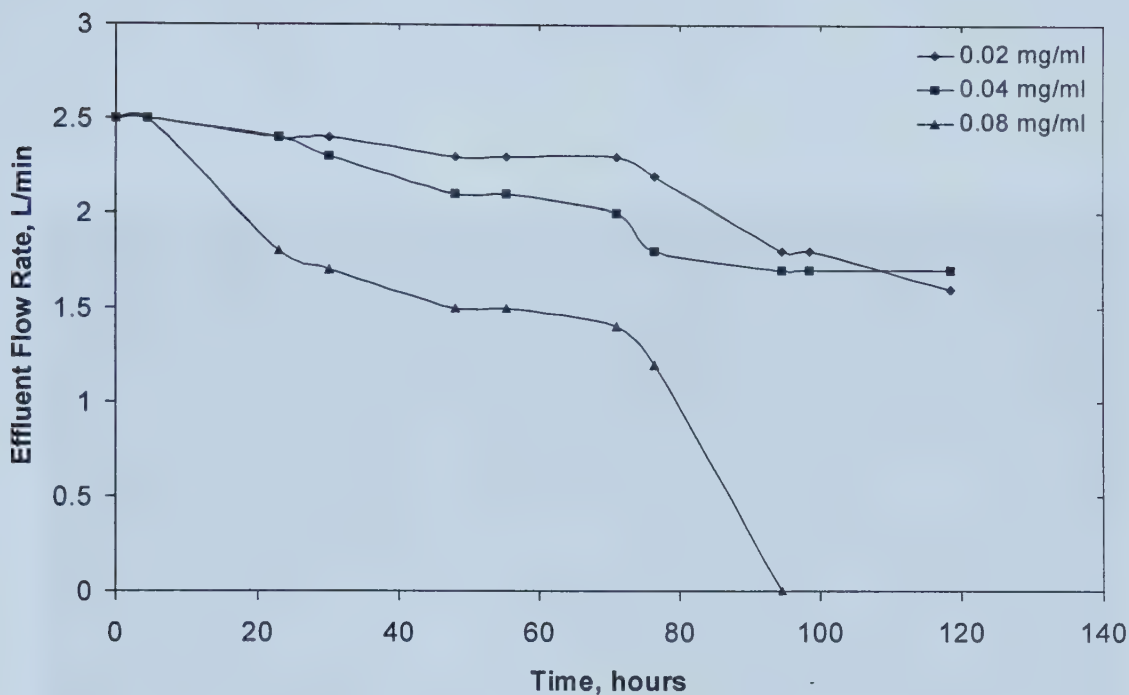

Figure 3.1b. Significance of Pol-E-Z-652 Polymer Concentration on Effluent Flow Rate at a Mixing Intensity of 1400 rpm using a 5 cm Diameter Paddle Impeller and Clarifier Basin as Influent Water Source.

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Figure 3.2a. Significance of Pol-E-Z-652 Polymer Concentration on Effluent Flow Rate at a Mixing Intensity of 250 rpm using a 5 cm Diameter Paddle Impeller and Stilling Basin as Influent Water Source.
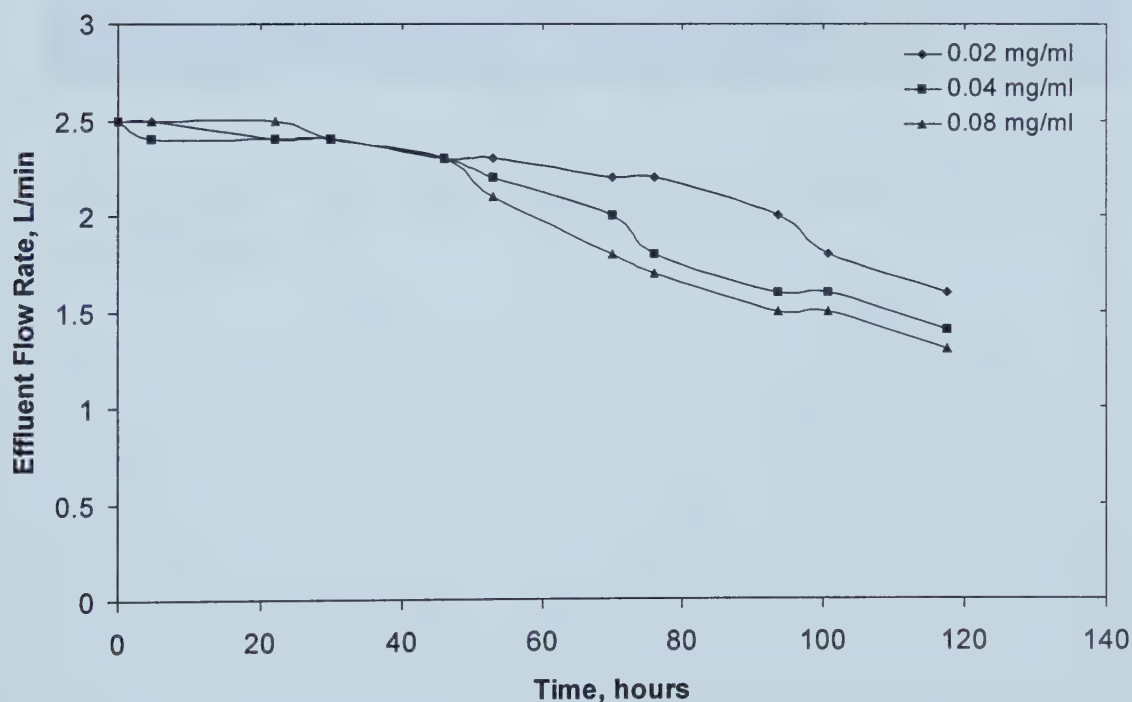

Figure 3.2b. Significance of Pol-E-Z-652 Polymer Concentration on Effluent Flow Rate at a Mixing Intensity of 1400 rpm using a 5 cm Diameter Paddle Impeller and Stilling Basin as Influent Water Source.

Figure 3.3a. Scanning Electron Microscope Image Showing Rossdale Water Treatment Plant Filter Media Completely Coated with Filter Aid Polymer (scale 1200 μm).

Figure 3.3b. Scanning Electron Microscope Image of Clean Filter Media From Pilot Plant (Scale 100 μm).
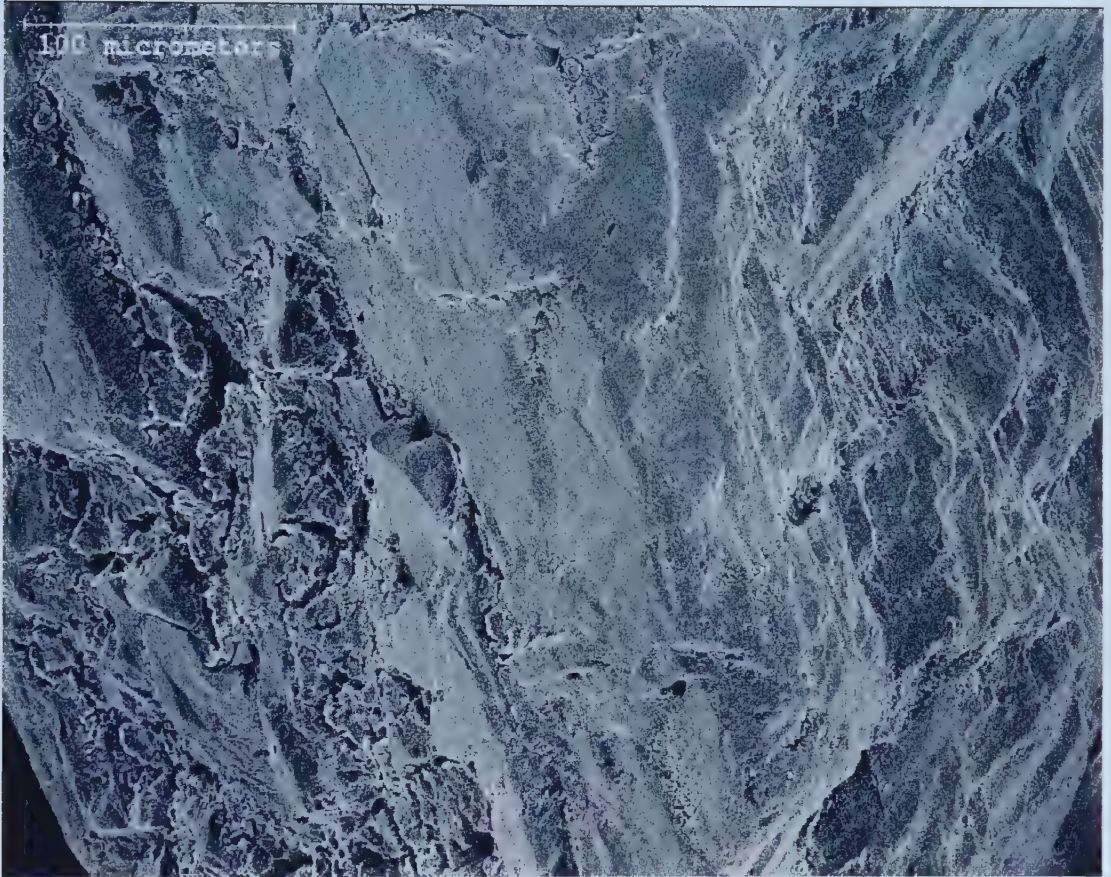
Figure 3.3c. Scanning Electron Microscope Image of Pilot Plant Filter Media with Small Deposit of Filter Aid Polymer (scale 100 μm).

Figure 3.3d. Scanning Electron Microscope Image Showing Rossdale Water Treatment Plant Filter Media Completely Coated with Filter Aid Polymer at a Higher Magnification (scale 100 μm).
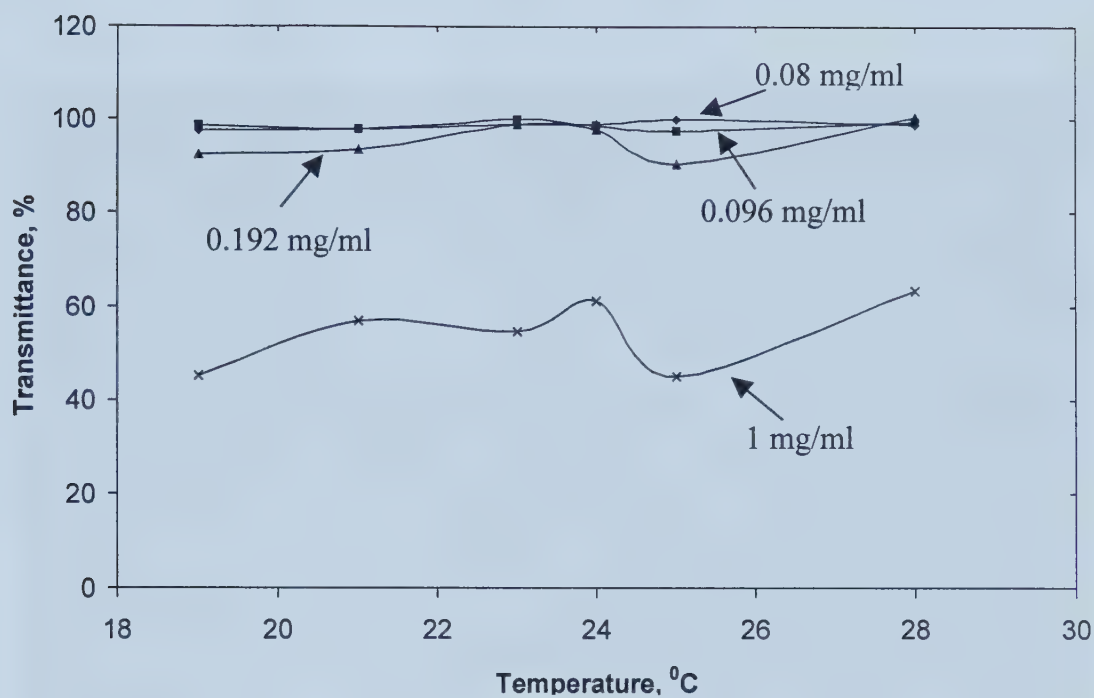
Figure 3.4. Cloud Point Data for Pol-E-Z-652 Polymer at Various Concentrations
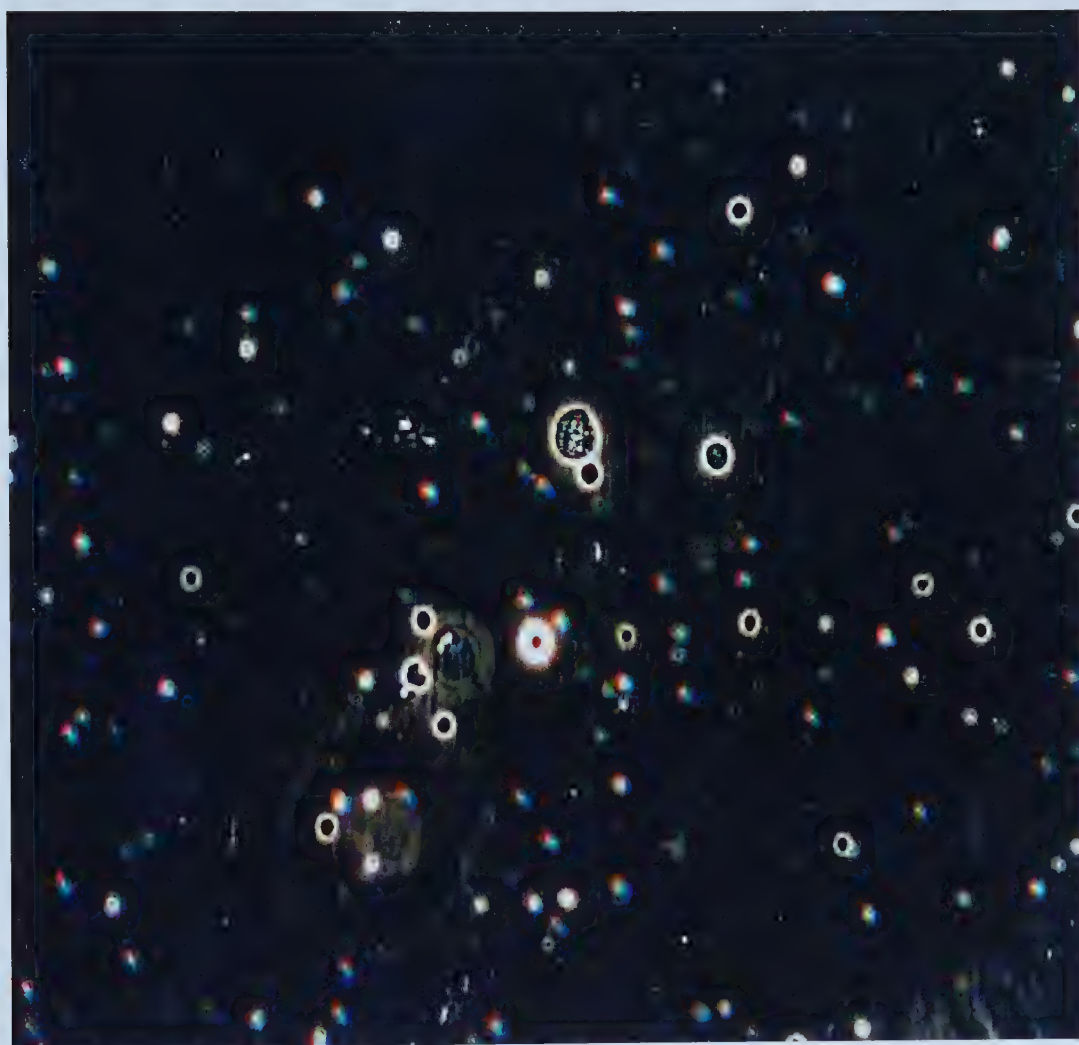
Figure 3.5a. Sample of Pol-E-Z-652 Stock Solution at a Magnification of 100 times.

Figure 3.5b. Sample of Pol-E-Z-652 Polymer at a Concentration of 0.08 mg/ml at a Magnification of 100 times.

Figure 3.5c. Sample of Pol-E-Z-652 Polymer at a Concentration of 0.04 mg/ml at a Magnification of 100 times.

Figure 3.5d. Sample of Pol-E-Z-652 Polymer at a Concentration of 0.02 mg/ml at a Magnification of 100 times.
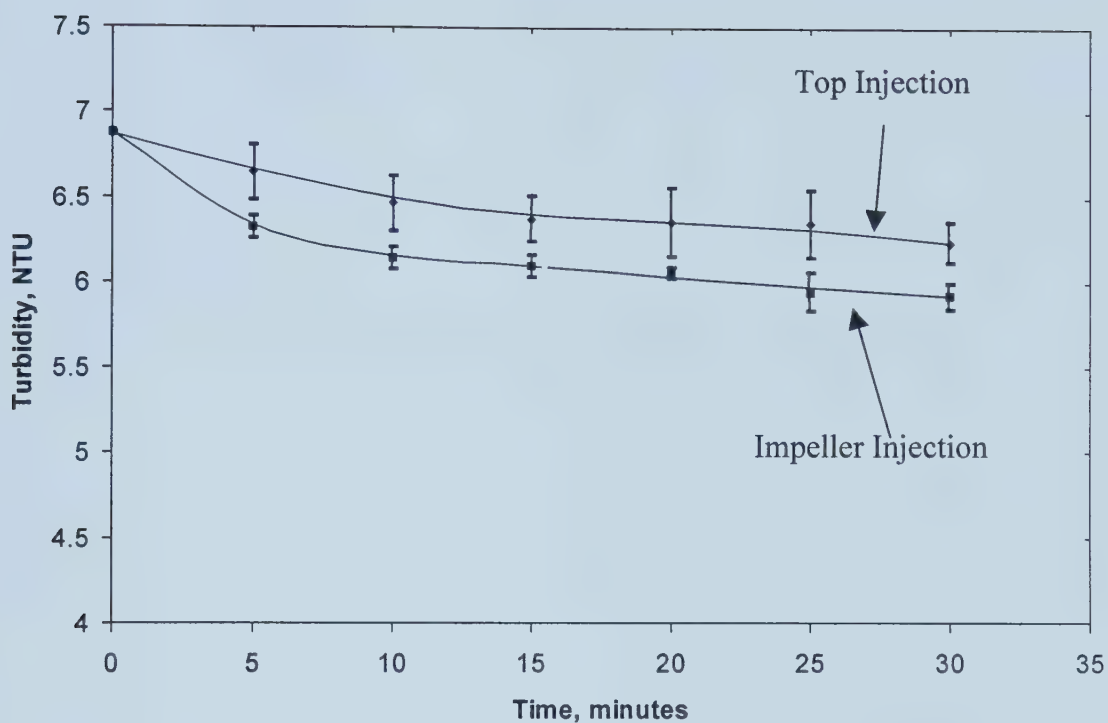
Figure 3.6a. Kinetics Data for Mixing Intensity of 370 rpm for Pol-E-Z-652 Polymer at a Concentration of 0.04 mg/ml using a 7.6 cm Diameter Paddle Impeller for Polymer Injection at Top of the Tank and at the Impeller.
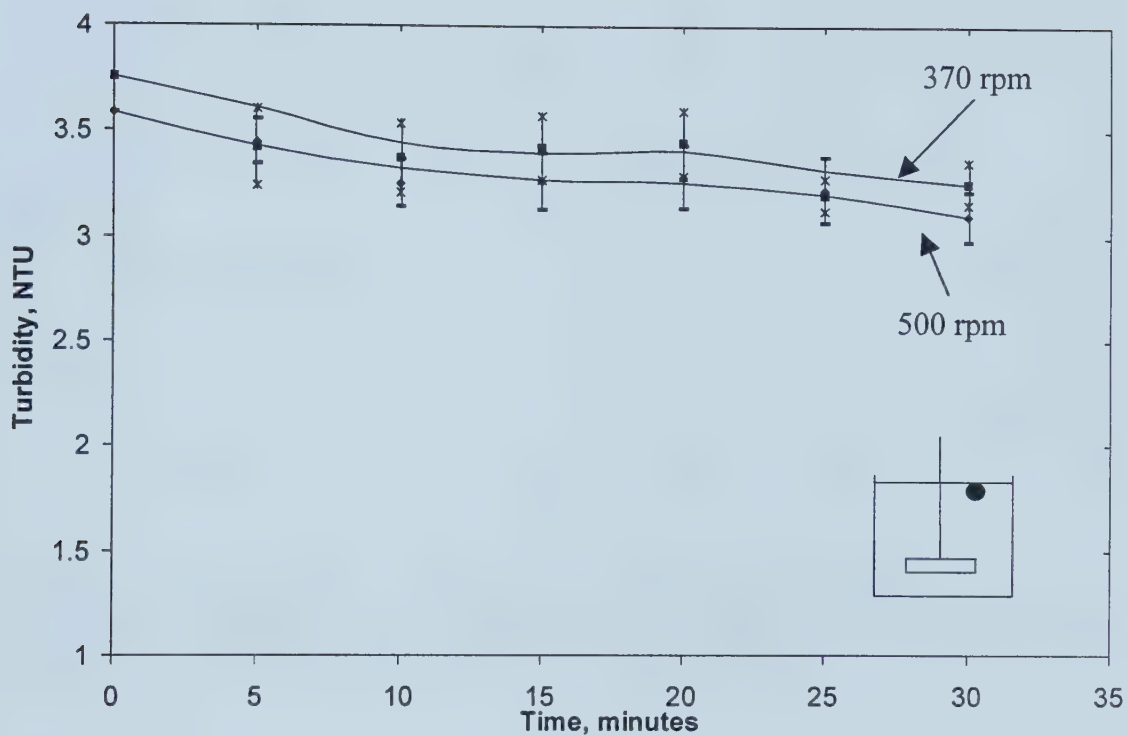
Figure 3.6b. Kinetics Data for Mixing Intensities of 370 and 500 rpm for Pol-E-Z-652 Polymer at a Concentration of 0.02 mg/ml using a 7.6 cm Diameter Paddle Impeller and Injecting Polymer at the Top of the Tank.

Figure 3.6c. Kinetics Data for Mixing Intensities of 370 and 500 rpm for Pol-E-Z-652 Polymer at a Concentration of 0.02 mg/ml using a 7.6 cm Diameter Paddle Impeller and Injecting the Polymer at the Impeller.
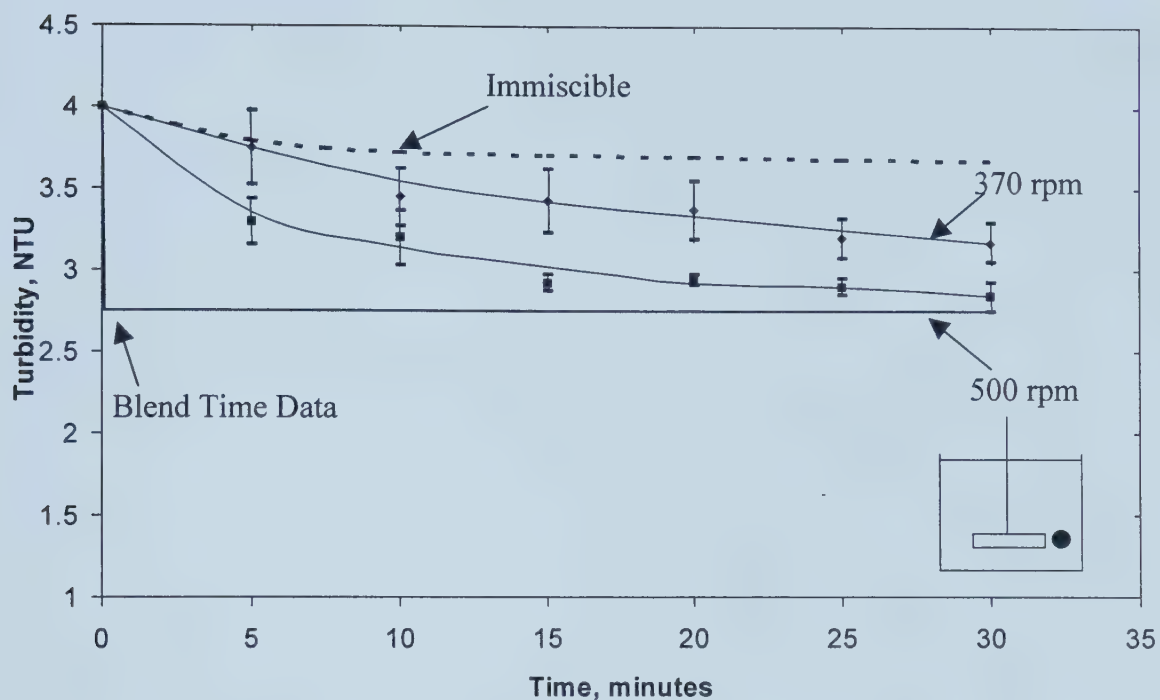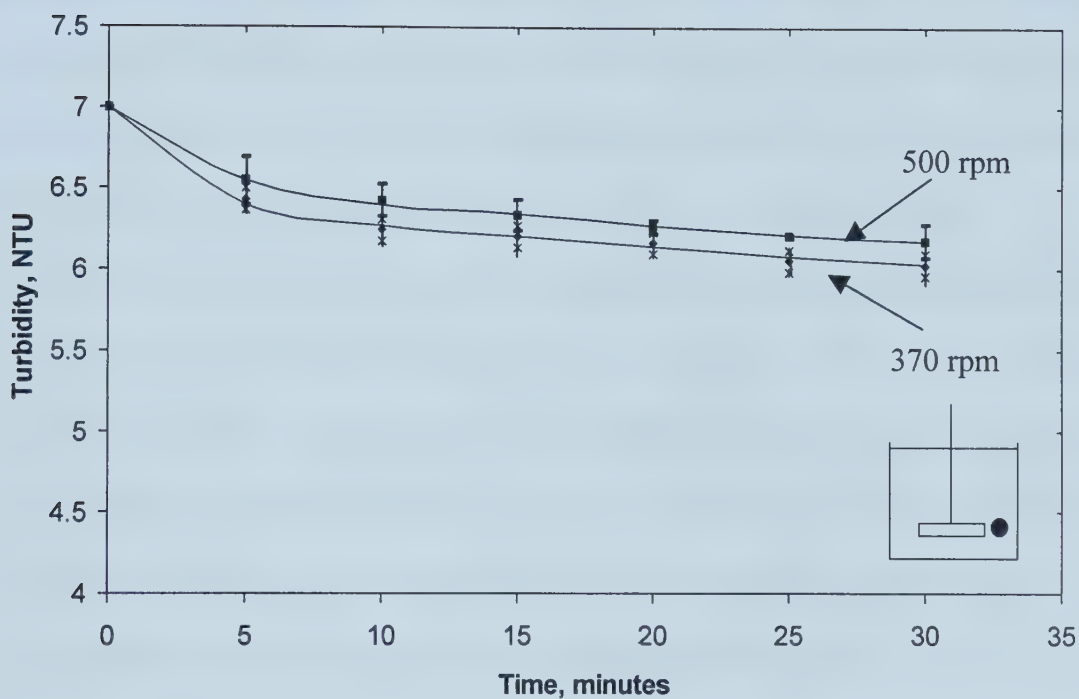
Figure 3.6d. Kinetics Data for Mixing Intensity of 370 and 500 rpm for Pol-E-Z-652 Polymer at a Concentration of 0.04 mg/ml using a 7.6 cm Diameter Paddle Impeller and Injecting Polymer at the Impeller

Chapter 4

Conclusions and Future Work

4.0 Conclusions

This study continued previous work on filter aid polymer usage in water treatment applications. This study specifically focused on the effect of mixing on the polymer and on the determination of physical properties of the polymer that affect the mixing. From the experimental results and analyses, the following can be concluded.

1. The mixing intensity used to mix the polymer in the mixing tank had a significant effect on the filter performance. This is consistent with previous studies performed on filter aid polymers in water treatment. However, these results are only applicable when water from the clarifier basin was used. When water from the stilling basin was used in the pilot plant experiments, mixing became a secondary factor as chlorination has an impact on the filter runs.

2. The dosage of the polymer has a direct effect on the filter performance. As the polymer dosage is increased, the headloss development in the filter increases and results in short filter run times. This applies to both water sources. Effect of concentration was seen for all three concentrations tested when the clarifier water was used but when the stilling basin water was used, only at the highest concentration was an effect seen.

3. The headloss profile across the filter media suggests that the polymer is blocking the pores at the top of the filter and creating a cap on the top of the filter. The headloss profiles indicate that depth penetration is not the main phenomena occurring in the filters.

4. Scanning electron microscope pictures showed that the polymer is depositing on the filter media. This indicates that the detachment mechanism is incomplete and that the polymer is coating the surface of the filter media. This contributes to the decline in filter performance over time.

5. Viscosity of the polymer feed solution does not adversely effect the mixing time required for homogeneous conditions as the polymer solutions used have viscosities close to water at 20^0C. Viscous mixing is not a factor in the current study.

6. The polymer used in the experiments was found to be completely soluble given long time spans (24 hours). However, the polymer is partially miscible at short time spans as seen in the microscope pictures of the initial polymer dilution and the kinetics study. Even though the polymer is water soluble, there is a kinetic effect which increases the time required to fully disperse the polymer. In the blending of two identical fluids, a vessel is assumed to be back-mixed at a ratio of the residence time in the tank to blend time of 5:1 to 10:1. However, if the system contains a polymer, this may not hold true as this study found that for this specific polymer-water system that a ratio of 75:1 was required to achieve consistent results. When this ratio is compared to the time of the kinetics experiments, it was found that this is equal to the 50% mixed time. The resistance to dispersion could be the result of polymer coils overlapping resulting in more mixing time required to separate them into single polymer chains.

7. To achieve optimum dispersion in the mixing tank, the polymer solution should be fed near the impeller where the area of highest turbulence occurs. Feeding at

the impeller increases the polymer drop break up due to the trailing vortices that are formed. This faster reduction in polymer drop size increases the rate of molecular diffusion.

4.1 Future Work

While this study opens a new area of discussion in the blending of soluble polymer additives that behave like liquid-liquid systems, there are several areas that still need to be investigated. This study defined the kinetics for one specific polymer-water system. It would be beneficial to define the kinetics of other polymer-water systems to determine how the kinetics vary with polymer type, molecular weight, charge etc. One of the main roadblocks in this study was the lack of information available from the vendors on the properties of the supplied polymer solutions. Many assumptions were made on the limited information provided by the vendor which caused confusion about some of the results. A great deal of difficulty arose due to the uncertainty in the exact properties of the polymer. Future work should include studies into the molecular weight, intrinsic viscosity and overlap concentrations of the polymer solutions to determine the exact configuration of the polymer in solution. This configuration could help explain the resistance to dispersion and provide insight into the best practice for using the polymer. The Flory-Huggins model may help in defining the thermodynamic properties of the polymer solutions. As well, investigating the properties of polymers supplied in emulsion form would be beneficial. This would help to understand what happens when the "water-soluble" polymer emulsion is diluted in water and what happens to various components of the emulsion in solution. It would also be of interest to determine the exact amount of

polymer that is contained in the emulsion. This would give a better indication of the true polymer concentration used for particle capture.

Appendix I.

Pilot Plant Operating Procedures

I.1 Starting a Run

Figure I1 shows the valve arrangement for the pilot plant.

1. Open filter influent valve, B, and overflow valve, E, on the filter.

2. Open the water intake valve, A, on the inlet to the mixing tanks to start water flow (check the flow meter to ensure that the flow rate is approximately 3 liters per minute).

3. Open the filter effluent flow valve, H, to the right (discharge mode).

4. Adjust the valve D to ensure that the flow rate of 2.5 liters per minute is being obtained.

5. Start the polymer injection pump and ensure that the suction end of the hose is located at the bottom of the cylinder containing the polymer and the discharge end of the hose in located under the impeller in the mixing tank.

6. Open the piezometer valves, HL, located on the side of the filter.

7. Turn on mixers and adjust the rotational speed.

8. Turn on particle counter and turbidimeters and start the computer.

I.2 Shut Down and Backwash Procedure

1. Stop the computer and save the data. Turn off particle counters and turdimeters

2. Shut off the polymer injection pump and turn off mixers.

3. Close the water intake valve, A.

4. Ensure valve D is open so the water from filter can discharge to drain.

5. Close the filter influent valve, B and the piezometer valves, HL.

6. Ensure filter effluent flow valve, H, is open (to the right) to drain water from the filter. Let the water drain from the filter until it about 50 cm over the media.

7. Close filter effluent flow valve, H.

8. Open valve air injection valve, G, to start the sir scouring and let it run for 3 minutes.

9. When the air scouring is finished, turn the filter effluent flow valve, H, to the left. Open the backwash water valve, C, slowly and close the air injection valve, G.

10. Gradually increase the backwash flow until the sand bed is fluidized completely. Ensure that the backwash water flow does not wash filter media out the overflow valve.

11. Backwash at this rate for 10 minutes and then gradually reduce the backwash water flow rate to settle the media evenly.

12. After the backwash is finished, close the backwash water valve, C and close the filter effluent flow rate valve, H.
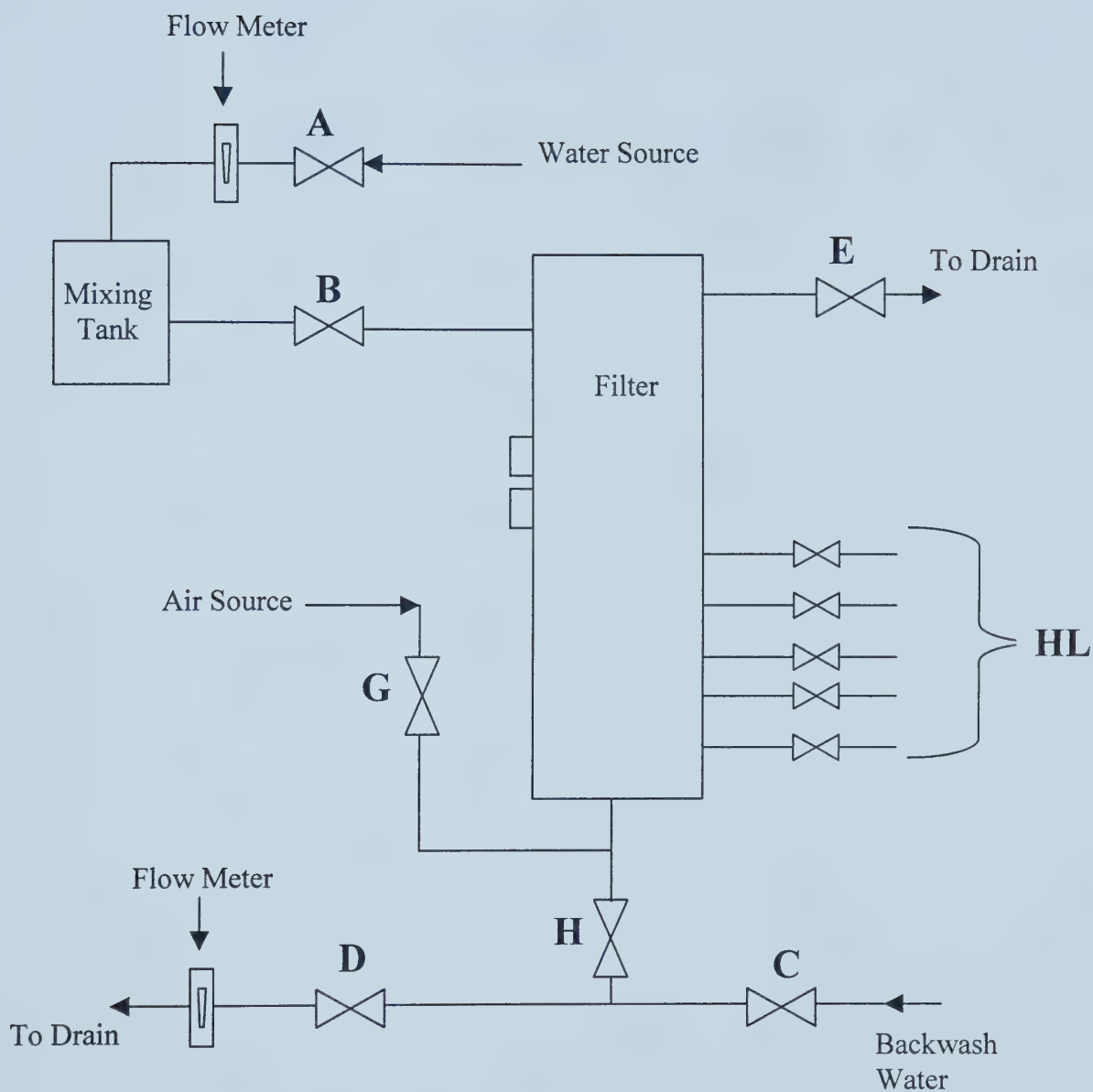
Figure I1. Valve Arrangement for Pilot Plant

Appendix II

Calculation for Polymer Concentration

The filter aid polymer used at the pilot plant was fed from a 2L supply using a peristaltic pump. The vendor supplied polymers solutions were used to make a 1g/L stock solution. This stock solution was diluted to make a working solution where

$$(C\,V)_{stock} = (C\,V)_{working} \qquad (1)$$

The product of the desired filter effluent concentration and effluent volumetric flow rate will equal the concentration of polymer required multiplied by the volume of the working solution. To determine the amount of polymer (X) required to achieve a dose of 0.04 mg/L Pol-E-Z-652 fed in 1.8 L over a 24 hour period, the calculation is as follows

$$(C\,V)_{effluent} = (C\,V)_{working} \qquad (2)$$

$$0.04 \text{ mg/L} * 3 \text{ L/min} * 1440 \text{ min/day} \quad = \quad X \text{ mg/L} * 1.8 \text{ L/day}$$

This value X is the amount of polymer to be added into the working solution per liter. To create a 2 L working solution, this value needs to be doubled.

Appendix III

Sample Calculations for Viscometer

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To determine the kinematic viscosity of the polymer solution in centipoise, the time it took for the solution to flow through the capillary viscometer was multiplied by the calibration constant for the viscometer. A sample calculation is given below.

Sample Calculation

    Sample: 0.096 mg/ml Pol-E-Z-652 Polymer

    Time a) 1 min 16.05 s

          b) 1 min 16.25 s

    Mean time $\bar{t}$ = 1 min 16.15 = 76.15s

    Kinematic viscosity = $\bar{t}$ * 0.01426 = 76.15 *0.01426 = 1.08 cp

Appendix IV

Equation for Transmission Calculation for Spectrometer

Transmission is the percentage of energy passed through the system relative to the amount of light that passes through the reference. The OOIBase software for the spectrometer uses the following equation to determine the transmission of light through the sample which is expressed as a percentage relative to a standard substance.

$$\%T_\lambda = \frac{S_\lambda - D_\lambda}{R_\lambda - D_\lambda} x100\%$$

S_λ - sample intensity if each pixel, D_λ = dark intensity of each pixel, R_λ = reference intensity of each pixel.

Appendix V

Confidence Interval Sample Calculations for Kinetics Study

To determine the confidence interval for the kinetic dispersion data, four sample points were used: two from the original and two from the repeat experiments. The confidence interval was calculated using Excel. Below is a sample calculation for determining the confidence interval including the equation that was used.

Sample Calculation

Sample: 0.04 mg/ml Pol-E-Z-652 Polymer at 500 rpm at Time = 5 minutes

	Sample 1 Turbidity	Sample 2 Turbidity
Run #1	6.45	6.65
Run #2	6.51	6.35

Mean $\bar{x} = \dfrac{1}{n}\sum x_i = \dfrac{6.45 + 6.65 + 6.51 + 6.35}{4} = 6.49$

Variance $\sigma^2 = \dfrac{1}{n-1}\sum \left(x_i - \bar{x}\right)^2 = 0.0156$

Standard Deviation $= \sigma = 0.125$

Confidence Interval $= \bar{x} \pm z^* \dfrac{\sigma}{\sqrt{n}} = \underline{6.49 \pm 0.148}$

Where n is the sample size and for 90% confidence level, $z^* = 1.645$ (Moore and McCabe, 1993).

Reference

Moore, D.S., and McCabe, G.P., 1993," Introduction to the Practice of Statistics",

W.H. Freeman and Company, USA.